APPENDIX G: THERMAL MODEL AND QM THERMAL/VACUUM TEST RESULTS

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1. THERMAL MODEL DETAILS

All FalconSAT-2 thermal modeling was done using the MatLAB/Simulink software package. A listing of this program is available on request but not included here in the interests of saving space and trees. The general approach and assumptions are discussed below.

1.1 Flux History Calculation Routine Model

The flux history calculation model is saved as Thermal_fluxhist.mdl. When the flux history model runs, it calculates the heat flux coming into the satellite due to insolation (direct solar radiation), Earth infrared radiation, and albedo (solar radiation reflected off of the Earth). The model calculates this flux and compiles a history of it with respect to time for each face of the spacecraft under the assumption that the spacecraft is a six-sided cube.

1.1.1 Flux History Calculation Routine I/O

The inputs to the flux history calculation routine are:

- Satellite Epoch COEs
- Epoch date and UT
- TOF (taken from simulation clock)
- Satellite ADCS method (Sun-tracking, velocity tracking, tumbling, or quaturnions)

The outputs from my flux history calculation routine are (output as charts & matrices):

- Insolation flux for each face with respect to time for an entire orbit
- Earth Infrared flux for each face with respect to time for an entire orbit
- Albedo flux for each face with respect to time for an entire orbit

There are several subsystems within the flux history calculation model. They are listed below, with their purpose, inputs, and outputs.

1.1.2 COE Update:

This subsystem updates the COEs from the epoch time to the current simulation time.

Inputs:	Outputs:
Epoch COEs	Updated COEs
Epoch Date/Time	Current Julian Date
Time of Flight	

1.1.3 Light:

This subsystem calculates the sun position vector, the satellite position and velocity vectors, and whether or not the satellite is currently illuminated by the sun.

Inputs:	Outputs:
Updated COEs	
Current Julian Date	
	R (satellite position vector)

V (satellite velocity vector)	Vis (illumination flag)
Rsun (sun position vector)	Satellite/Sun Angle

1.1.4 Surface Normals:

This subsystem calculates the surface normal vectors of the satellite assuming that the satellite is a six-sided cube. This routine is used if the satellite is sun-tracking, velocity-tracking, or tumbling. There is a switch where the user can choose which tracking mode to use. Alternatively, the surface normal vectors can be calculated using quaturnions. There is a switch that allows the user to choose which method of calculating the surface normal vectors they would like to use.

Inputs:	Outputs:
R (satellite position vector)	Surface Normal Vectors
V (satellite velocity vector)	(+X, -X, +Y, -Y, +Z, & –Z)
Rsun (sun position vector)	Phi (Angle from +K axis to R vector)
Vis (illumination flag)	Theta (Angle from +I axis to R vector)
Satellite/Sun Angle	

1.1.5 Insolation:

This subsystem calculates the insolation flux on each face of a satellite assuming that it is a six-sided cube.

Inputs:	Outputs:
Surface Normal Vectors	Insolation flux on each face (Wm^{-2})
Rsun (sun position vector)	
Vis (illumination flag)	

1.1.6 Earth Effects:

This subsystem calculates the Earth Infrared and Albedo flux on each face of the satellite assuming that it is a six-sided cube. This part of the model takes the longest time, as there is a double discrete summation to calculate the Earth IR and Albedo view factors.

Inputs:	Outputs:
Surface Normal Vectors	Earth IR flux on each face (Wm^{-2})
R (satellite position vector)	Albedo flux on each face (Wm^{-2})
Rsun (sun position vector)	Earth IR view factors for each face
Phi (Angle from +K axis to R vector)	Albedo view factors for each face
Theta (Angle from +I axis to R vector)	

1.1.7 Flux History Calculation Results:

The results from my simulation are charts of Insolation Flux, Earth IR Flux, and Albedo Flux. These various flux history outputs are also in matrix form, so that they may be used as inputs for the nodal temperature calculation model.

I verified these results with analytical calculations for the using the equations from *Space Mission Analysis and Design*, 3rd edition page 256. My results were further verified by comparing my flux history charts with data generated by Dr. Craig Underwood at the University of Surrey, UK for the SNAP nanosat using Pascal thermal model, which are in Figures 1b, 2b, and 3b.

1.2 NODAL THERMAL ANALYSIS MODEL:

The second model in the overall thermal analysis model is the portion that calculates the temperature at each node throughout the spacecraft using finite differential analysis. The model is broken down into several subsystems. The first is simply where the various nodes and constants for the model are input. The second calculates the heat coming to each node at each time step. This is where the flux histories previously calculated are used in this model. The third subsystem calculates the heat transfer between each node due to Fourier conduction. The fourth subsystem calculates the heat transfer between each node and space. These subsystems, taken together, represent all of the heat going into or out of every node. These are then fed into a routine that uses finite differential analysis to calculate the change in temperature at each node. The new temperature at each node is then calculated by adding the Delta T to the temperature at the node from the previous time step. The model then proceeds to the next time step. Once it has gone through enough orbits, the output of the model is a thermal profile of each node in the satellite through an entire orbit. Repeated calculations using varying initial conditions show that we must typically iterate through 13 – 14 orbits in order to get an accurate thermal model of the satellite.

There are several subsystems within the nodal temperature calculation model. They are listed below, with their purpose, inputs, and outputs.

1.2.1 External Qin:

This subsystem calculates the external heat transfer into each node due to insolation, Earth infrared, and albedo. The inputs are the flux history matrices compiled in the previous model. These are then adjusted using the geometry of the satellite structure to calculate the flux on each facet. Then, the flux on each facet is multiplied by the appropriate absorptivity or emissivity value for each node to calculate the external heat transfer into each node.

Inputs:	Outputs:
Insolation flux on each face	Qext – external heat coming into each node
Earth IR flux on each face	due to Insolation, Earth IR, and Albedo (W)
Albedo flux on each face	
SNAP-1 geometry	
Surface area of each node (m^2)	
Nodal thermo-optical properties (α,ε)	

1.2.2 Fourier Conduction:

This subsystem calculates the heat transfer between nodes due to Fourier conduction. It iterates through each node in the satellite and calculates the heat transfer to or from every other node. The key equation in this subsystem, with "i" being the current node of interest, is: $Q_{cond}(i) = \sum_{j=1}^{\max nodes} k(i,j) * \left(T(j) - T(i)\right)$, with the subsystem performing this summation for each of the nodes in the satellite.

Inputs:	Outputs:
k – thermal conductivities between nodes	Qcond – heat coming into each node due to
T – temperature of each node (K)	conduction from other nodes (W)

1.2.3 Black Body Radiation From Space:

This subsystem calculates the black body radiation coming into each node from the background of space. Of course, heat is actually transferring out of each node to space, so the outputs from this subsystem will be negative. The heat transfer from each node to space is calculated using the black body radiation equation, with the background heat of space assumed to be 4K.

<u>Inputs</u>:
IR Emissivity (ε) of each node
T – Temperature of each node (K)
Surface area of each node (m^2)
Background temperature of space (4K)
Stefan-Boltzmann constant

<u>Outputs</u>:
Qspc – heat coming into each node due to black body radiation from space (W) – this is a negative value as heat is transferring out of each node and radiating TO space

1.2.4 Internal Power Dissipation:

This subsystem puts the internal power dissipated at each node into the matrix form the model requires. These internal power dissipations are an input to the overall thermal model.

<u>Inputs</u>:
Internal power dissipated at each node (W)

<u>Outputs</u>:
Qint – internal power dissipated at each node as heat (W)

1.2.5 Finite Differential Analysis:

This subsystem calculates the temperature of each node using finite differential analysis. The key equation in this subsystem is: $\Delta T = \frac{(Qext + Qcond + Qspc + Q\,\mathrm{int})}{(m * c)} * dt$. Once the Delta T at each node is calculated, the temperature at each node is calculated by adding the Delta T to the previous nodal temperature.

<u>Inputs</u>:
Qext – external heat coming into each node due to Insolation, Earth IR, and Albedo (W)
Qcond – heat coming into each node due to conduction from other nodes (W)
Qspc – heat coming into each node due to black body radiation from space (W)
Qint – internal power dissipated at each node as heat (W)
M – mass of each node (kg)
C – Specific heat capacity ($Jkg^{-1}K^{-1}$)
T – temperature of each node (K)
dt – time step (seconds)

Outputs:
Delta T – temperature change at each node (K)
T – temperature of each node (K)

1.2.6 Nodal Temperature Calculation (Finite Differential Analysis) Results:

The temperatures of each node are converted from K to degrees C, by subtracting 273.15 as the conversion factor. The temperature of each node is then plotted versus time on a scope. Additionally, the temperatures of each node are broken up and plotted on different scopes so that one can view the temperature of each node versus time.

2. SIMULATED FALCONSAT-2 NOMINAL ON-ORBIT THERMAL BEHAVIOR

Once we decided on the thermal design for FalconSat-2, we ran a simulation to determine the predicted nominal on-orbit thermal behavior of the satellite.

2.1 NOMINAL THERMAL BEHAVIOR:

We ran the thermal model with the thermal tape design implemented on the Flight Model as described in Section 2 of this CCD. The results are very encouraging. The thermal behaviors of most components are raised slightly in temperature, but are still within our desired nominal temperature ranges.

2.1.1 ASSUMPTIONS:

- Epoch Date = 21 January 2003, 0:00.00 UT
- Epoch Classical Orbital Elements: (ISS COEs)
  - Semi-major axis (a) = 6740 km
  - Eccentricity (e) = 0.0003
  - Inclination (i) = 51.58 deg
  - Right Ascension of the Ascending Node (Ω) = 90 deg
  - Argument of Perigee (ω) = 0 deg
- -Z facet is velocity-tracking due to drag

2.1.2 RESULTS:

The results of the FalconSAT-2 thermal simulation with the thermal tapes implemented are shown on the next page. Figure A-1 shows the behavior of the four solar panels. As can be seen, they did not change greatly from the baseline design and vary in temperature between –15ºC and +50ºC. Figure A-2 shows the thermal behavior of the internal module boxes and battery. The modules vary in temperature between +3ºC and +10.5ºC. The batteries vary between +5ºC and +8.5ºC. These results show that our thermal tape design will maintain all components of the satellite within the desired limits.

2.1.3 Key Performance Parameters:

Solar Panel Temperatures: –15ºC to +50ºC
Modules: +5ºC to +12.5ºC
Batteries: +7ºC to +11ºC

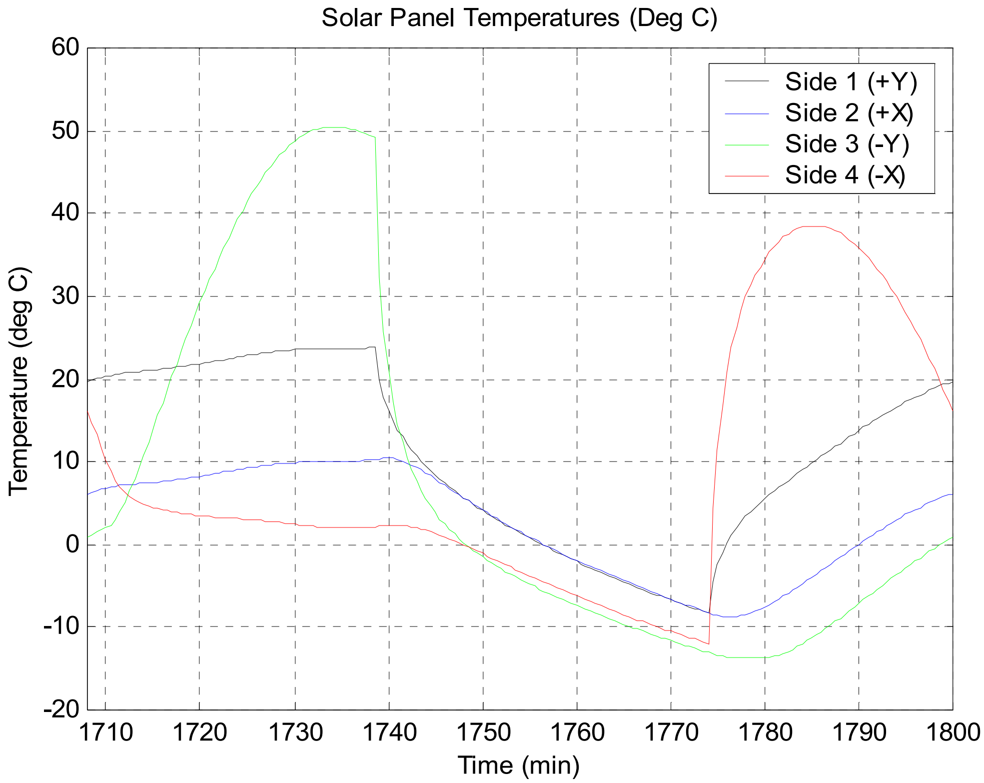

Figure A-1 – Predicted solar panel thermal behavior with thermal tape

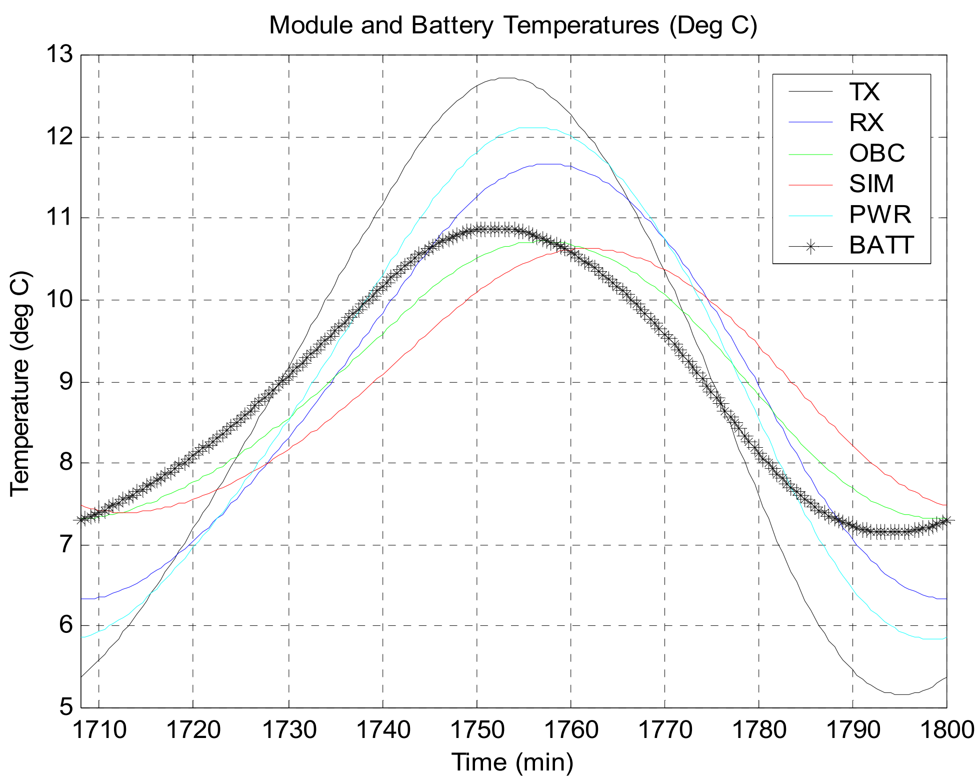

Figure A-2 – Predicted module box and battery thermal behavior with thermal tape

2.2 SIMULATED FALCONSAT-2 WORST-CASE HOT AND COLD ON-ORBIT THERMAL BEHAVIOR

For the worst-case thermal scenarios, we varied two things: time of year and side locked toward the sun.

We varied the time of year as follows:
- Spring Equinox (21 March 2003)
- Summer Solstice (21 June 2003)
- Fall Equinox (21 September 2003)
- Winter Solstice (21 December 2003)

We varied the side locked toward the sun as follows:
- +Z locked toward sun
- -Z locked toward sun
- +X locked toward sun (same behavior as –X)
- +Y locked toward sun (same behavior as –Y)

We thus ran four simulations for each date, for a total of sixteen simulations.

The absolute worst-case hot case is the Winter Solstice with +Y facet (Spacequest solar panel facet) locked toward the sun, with the solar panels varying between -10 and +60 deg C, and the batteries varying between +12 and +16 deg C. This is shown on the next page in Figures B-1 and B-2. The absolute worst-case cold case is the Spring Equinox with the +Z facet locked toward the sun, with the solar panels varying between -34 and -18 deg C, and the batteries varying between –24 and –21.5 deg C. This is shown on the next page in Figures G-3 and G-4.

Analysis of these simulation results shows that the worst-case hot case is not of great concern, as it is still within nominal operating temperature for the batteries. The worst case cold is of concern, as it is far below the minimum temperature limit. However, neither of these worst case situations are likely to happen, as they would mean either the +Z or –Z facet of the satellite is inertially locked toward the sun. FalconSat-2 is not likely to orient itself in this way in the first place, and if it does, our thermal tape design will cause the attitude to change due to solar radiation pressure torque.

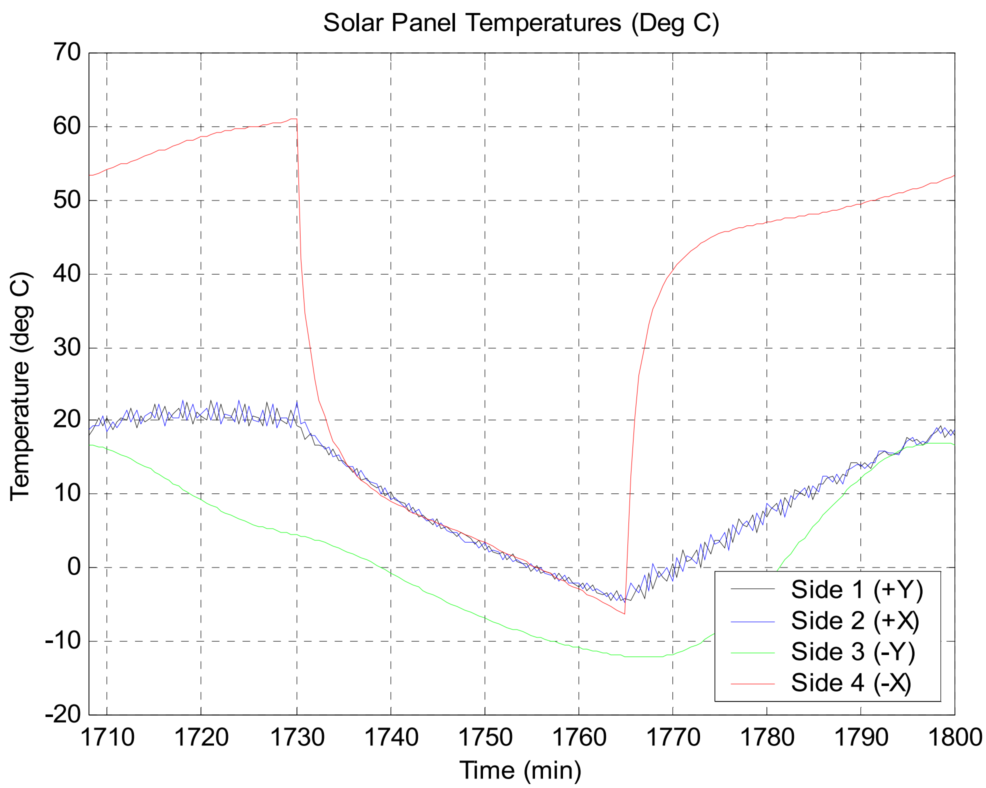

Figure B-1 –Worst-case hot solar panel thermal behavior

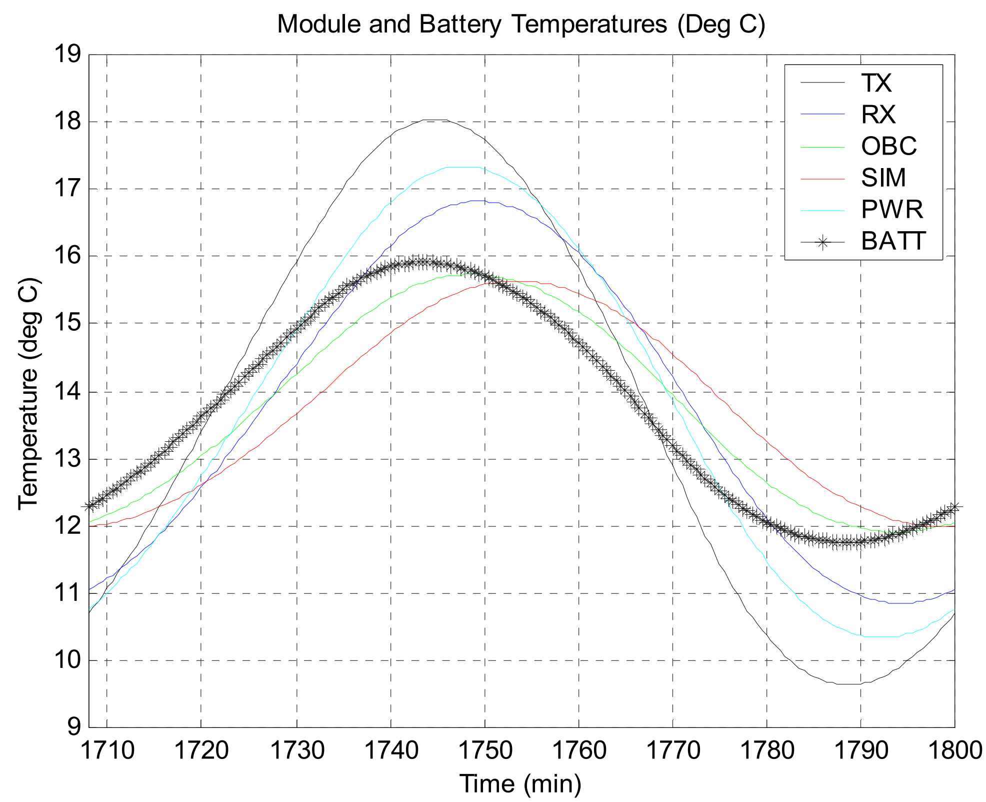

Figure B-2 –Worst-case hot module and battery thermal behavior

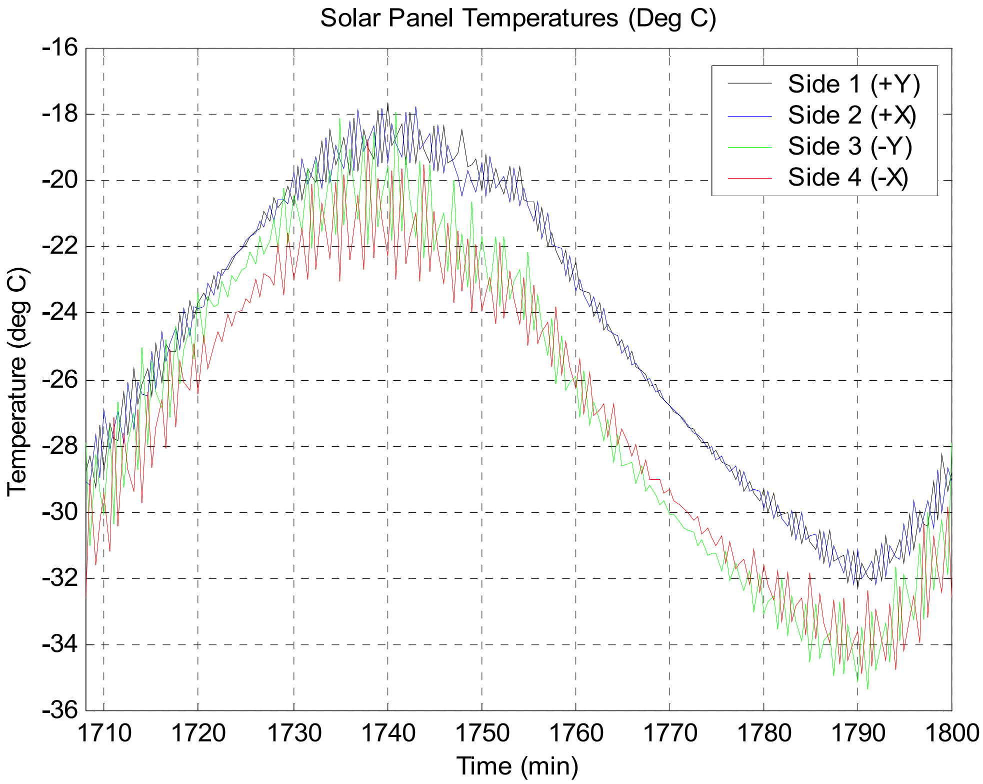

Figure B-3 –Worst-case cold solar panel thermal behavior

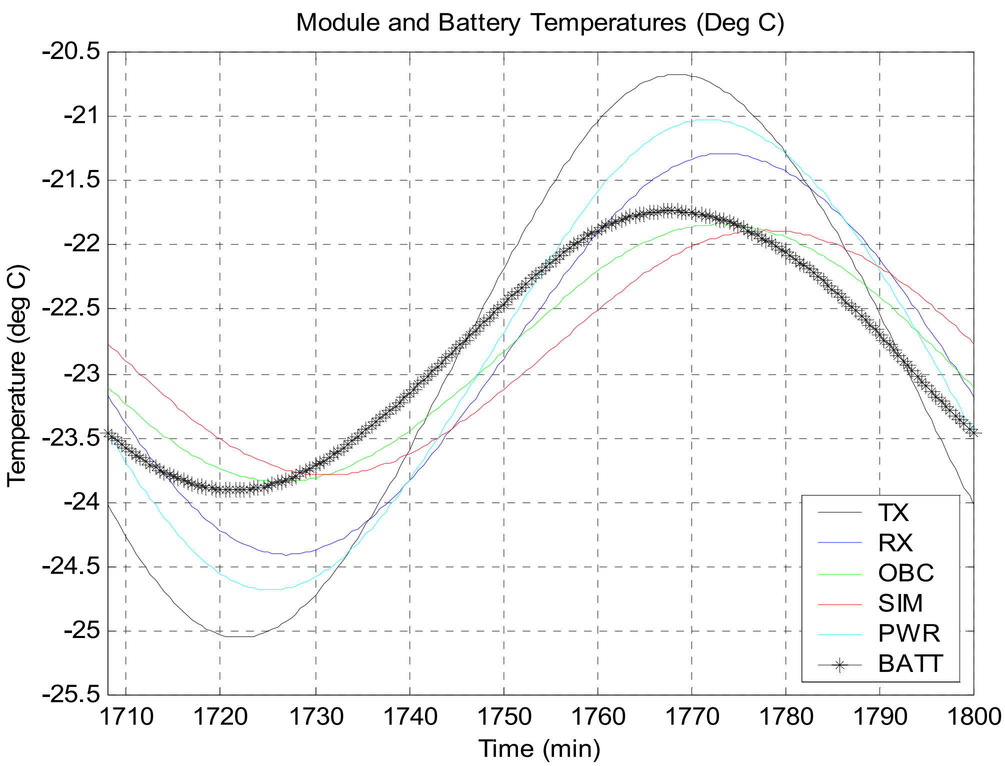

Figure B-4 –Worst-case cold module and battery thermal behavior

2.3 SIMULATED FALCONSAT-2 WORST-CASE HOT AND COLD COUPLED THERMAL BEHAVIOR

Working with the folks at Goddard Space Flight Center, FalconSat-2 will eventually be modeled using SINDA thermal modeling code. As a preparation for this, we have created a preliminary model of the case of FalconSat-2 coupled to the STS through the Get-Away Special (GAS) Canister via the Pallet Ejection System (PES).

2.3.1 INPUTS:

- The inputs to this thermal model are conduction value and boundary temperature values obtained from the thermal engineers at GSFC

- The boundary temperatures are from three attitude situations for the shuttle:
  - Bay-to-sun case (worst-case hot)
  - Bay-to-Earth case
  - Bay-to-space case (worst-case cold)

- We decided to look at the worst-case hot and cold cases. For this, we implemented the conductors and boundary temperatures for the bay-to-space case for the Worst-case-cold situation. This is because the shuttle could theoretically have its bay pointed toward space for an indefinite period of time. For the worst-case-hot case, we implemented the conductors and boundary temperatures for the bay-to-sun case for 60 minutes and the bay-to-earth case for 30 minutes per orbit. This is because the shuttle's orbit has a 30 minute eclipse, so the bay-to-sun case can only happen for a maximum of 60 minutes per orbit, and during the other 30 minutes of the orbit, the worst-case-hot will be the bay-to-earth case. We ran the model, and determined the point at which the batteries reached their storage temperature limits.

2.3.2 RESULTS:

- Bay-to-sun case (Worst-case-hot):
  - The batteries reach the maximum storage limit of 50°C in 240 minutes (in the third orbit cycle of a worst-case-hot condition)
  - The module boxes reach the maximum storage limit of 50°C in 150 minutes (in the second orbit cycle of a worst-case-hot condition)
  - Results are shown in Figure C-1.

- Bay-to-space case (Worst-case-cold):
  - The batteries never reach the minimum storage limit
  - The module boxes never reach the minimum storage limit
  - Results are shown in Figure C-2.

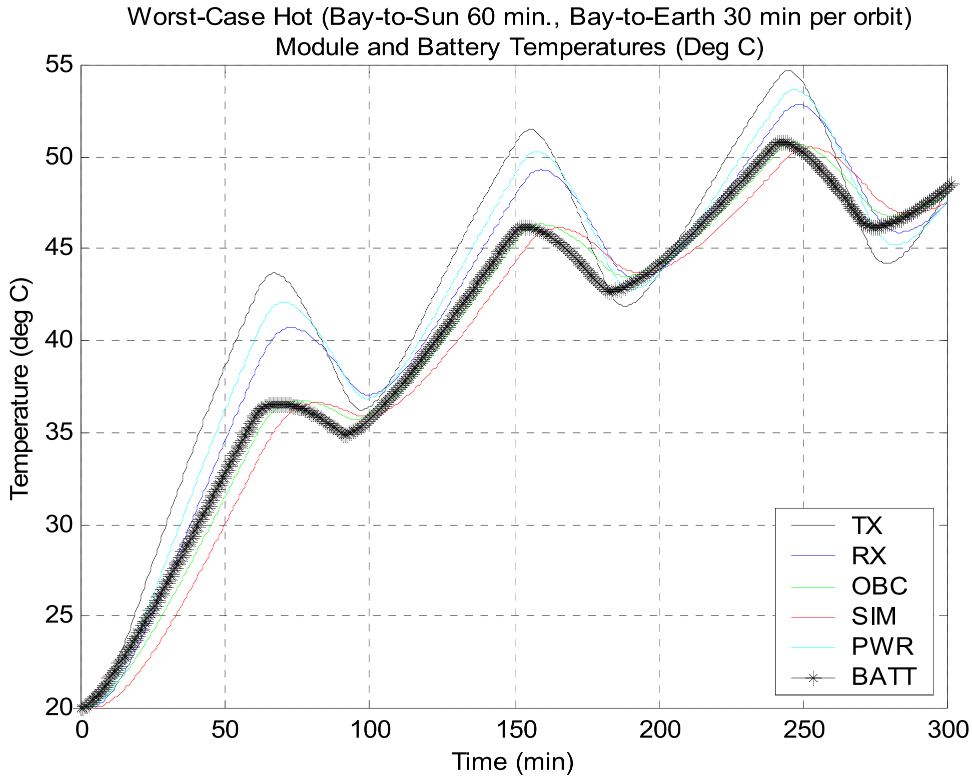

Figure C-1 –Bay-to-sun coupled case (Worst-case hot coupled thermal behavior)

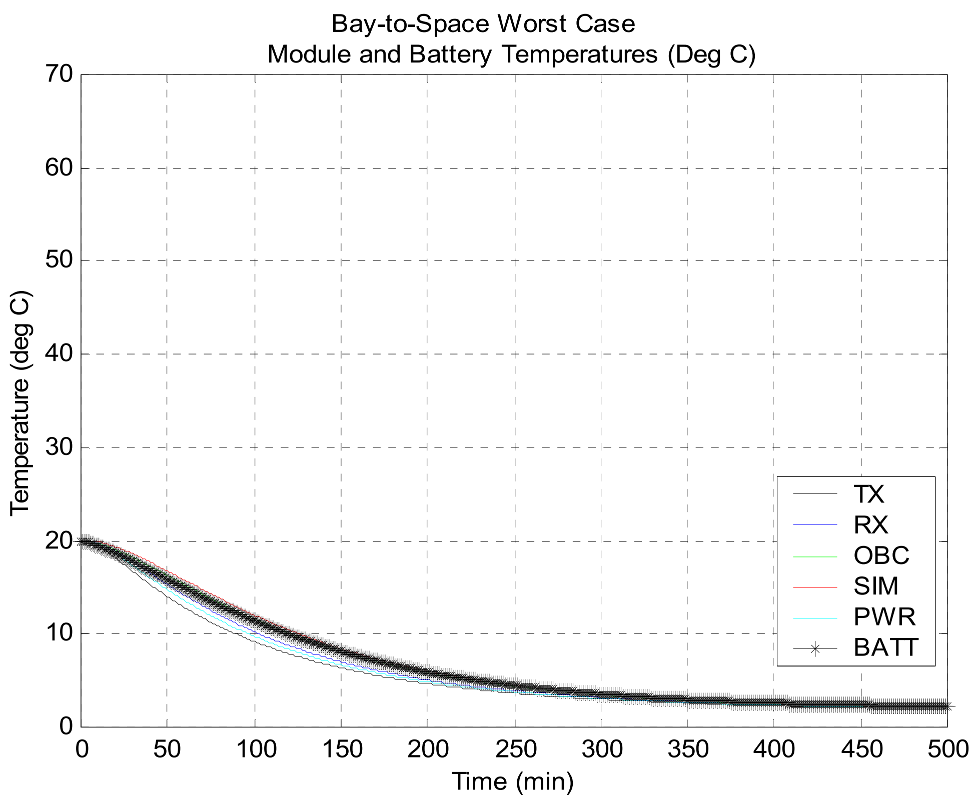

Figure C-2 –Bay-to-space coupled case (Worst-case cold coupled thermal behavior)

3. FALCONSAT-2 THERMAL/VACUUM TEST RESULTS:

The FalconSAT-2 Qualification Model Thermal/Vacuum test had three main parts. These parts are:

1) Hot Soak at +40 deg C and Cold Soak at –20 deg C

2) Ramp Up to +40 deg C and Ramp Down to –20 deg C two more times

3) Sun Cage Cycles: (bottom panel illuminated with albedo and earthshine)

    a. 1 orbit with side 1 illuminated

    b. 1 orbit with side 2 illuminated

    c. 1 orbit with side 3 illuminated

    d. 1 orbit with side 4 illuminated

    e. 1 orbit with each side illuminated for 15 minutes

The file FS2_QM_TVAC_plots.doc contains plots of the temperature vs. time for various parts of the satellite in each of the three parts of the thermal/vacuum test, and can be found in the Appendix of this CCD.

3.1 ANALYSIS:

In the hot/cold soak and ramp up/ramp down parts of the test, the satellite behaved as predicted using the Qualification Model MatLab Thermal Model. Additionally, these portions of the test allowed us to refine the model by increasing the number of nodes in the model from 30 nodes to 40 nodes. Plots D-1 and D-2 show the temperatures from the old model, new model, and actual thermocouple for the battery for the hot/cold soak and ramp up/ramp down parts of the T/Vac test.

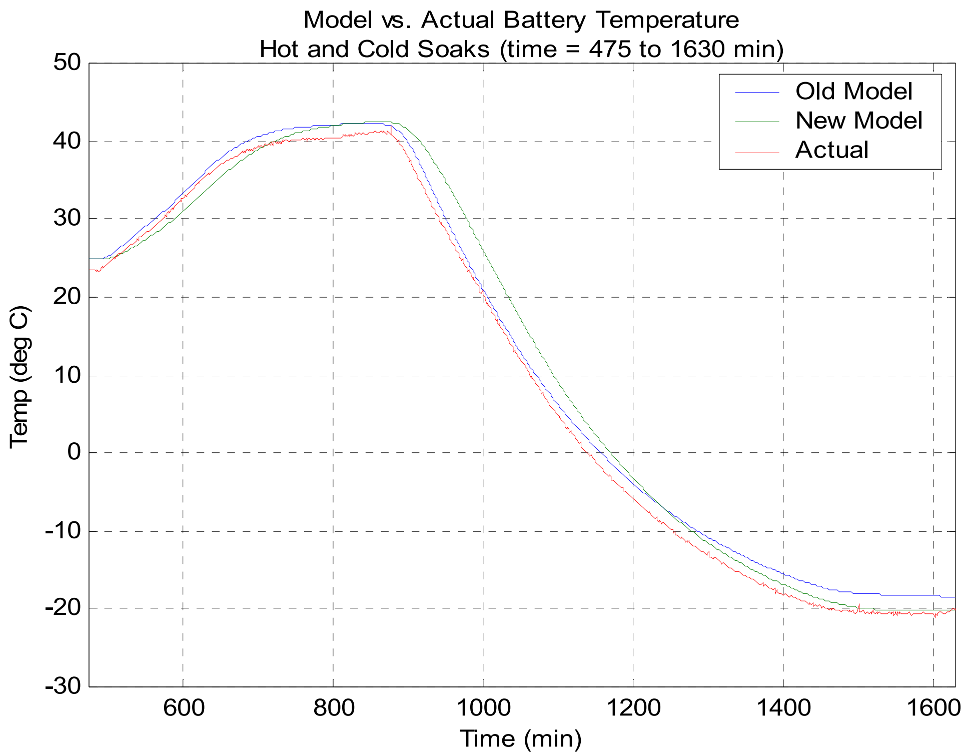

Figure D-1: Model vs. Actual Battery Temperatures for hot/cold soak

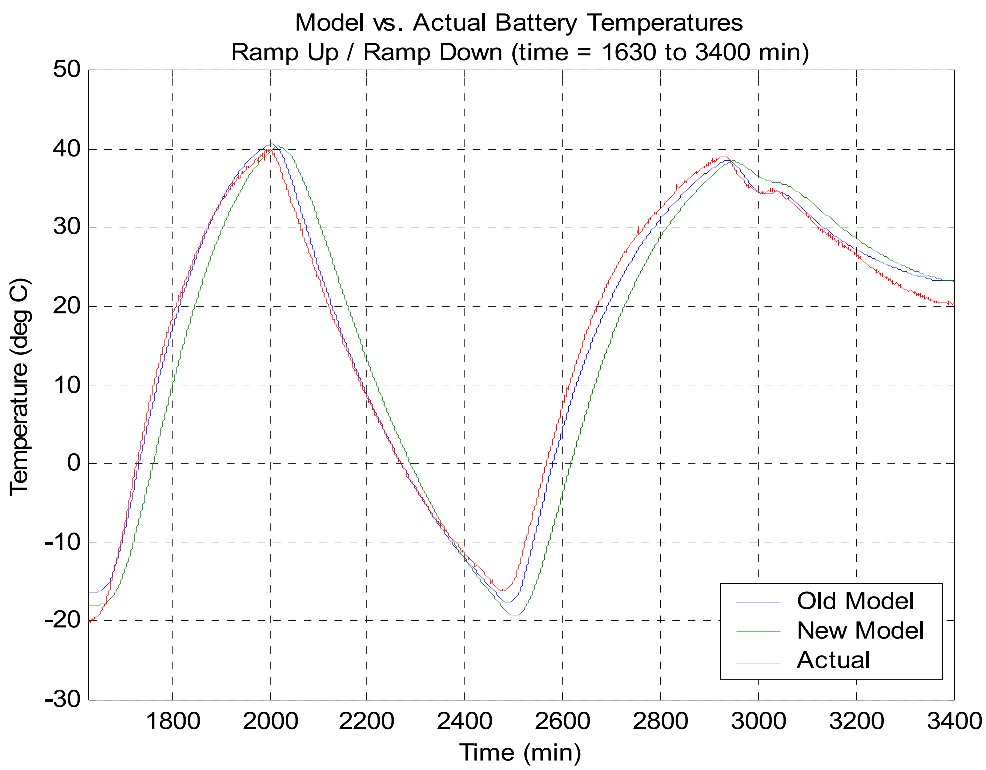

Figure D-2: Model vs. Actual Battery Temperatures for ramp up/down

In the sun cage cycles of the test, the satellite got very cold. The satellite started the sun cage cycles at +20 deg C. Of particular interest is how the battery behaved during the test; the battery dropped in temperature throughout the cycles, never reaching an equilibrium temperature. This behavior is very different from the behavior predicted by the Qual Model MatLab Thermal Model. To address the satellite's temperature drop, the refined nodal network (of 40 nodes) was put into the MatLab Thermal Model. The results show that the satellite does in fact run colder than predicted by the old nodal network. It appears that heat tends to flow around the outer structure of the satellite and be emitted as quickly as it is absorbed, rather than flowing into the inner column and electronics of the satellite. Figure A-3 shows the old model predicted temperatures, as well as the new model and actual battery temperatures for the sun cage cycles. As can be seen, the new test-validated model is correct, and a thermal redesign was required.

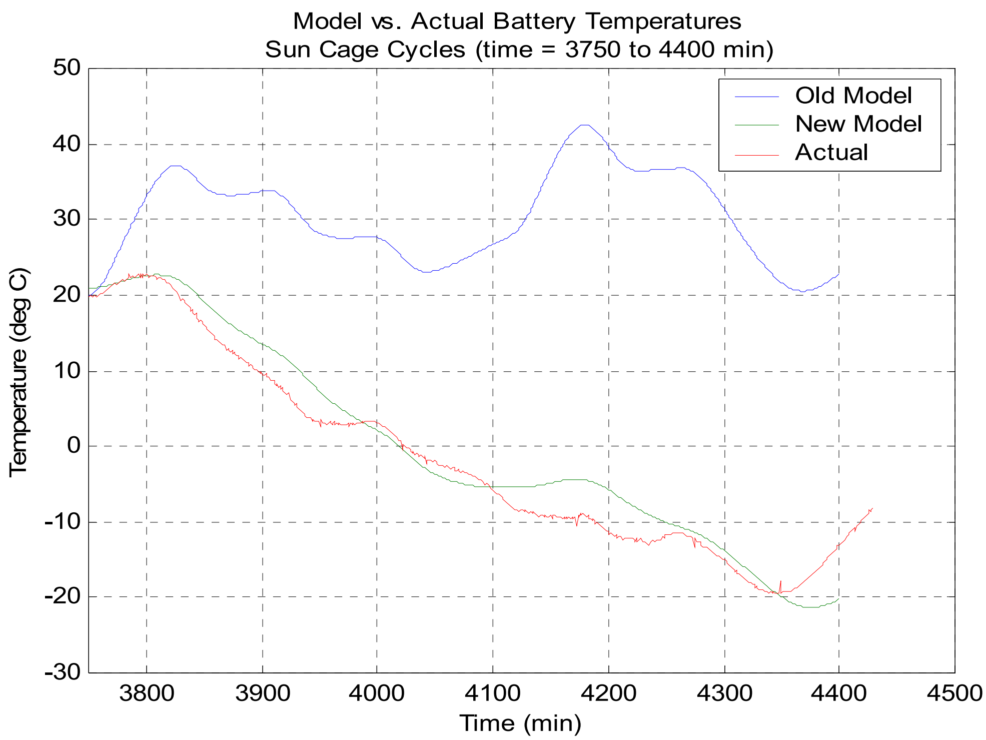

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Figure A-3: Model vs. Actual Battery Temperatures for sun cage cycles

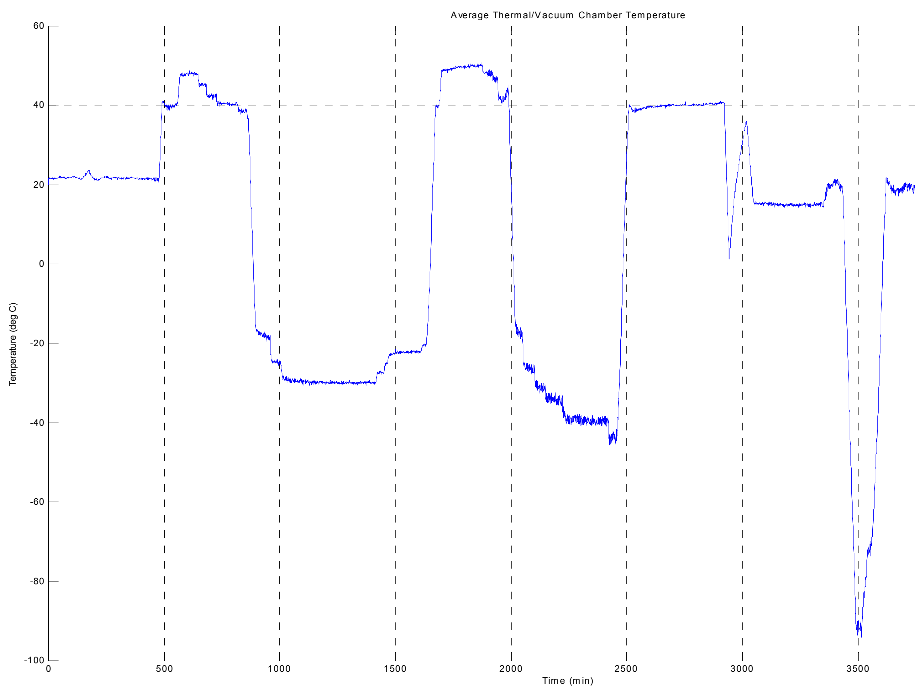
3.2 RECCOMMENDATIONS FROM QM THERMAL/VACUUM TESTING:

Running the Thermal/Vacuum Test on the FalconSAT-2 Qualification Model was critical to accurately characterize the thermal behavior of FalconSAT-2. Test validation allowed us to revise and correct the thermal model. The FalconSAT-2 thermal design needed to be revised to make the satellite run hotter. In the Qual Model design, the a/e ratio of the outer facets of the satellite was less than 1; in other words, the emissivity was higher than the absorptivity. To revise it, we needed to increase the a/e ratio by choosing different thermal tapes from Sheldahl.

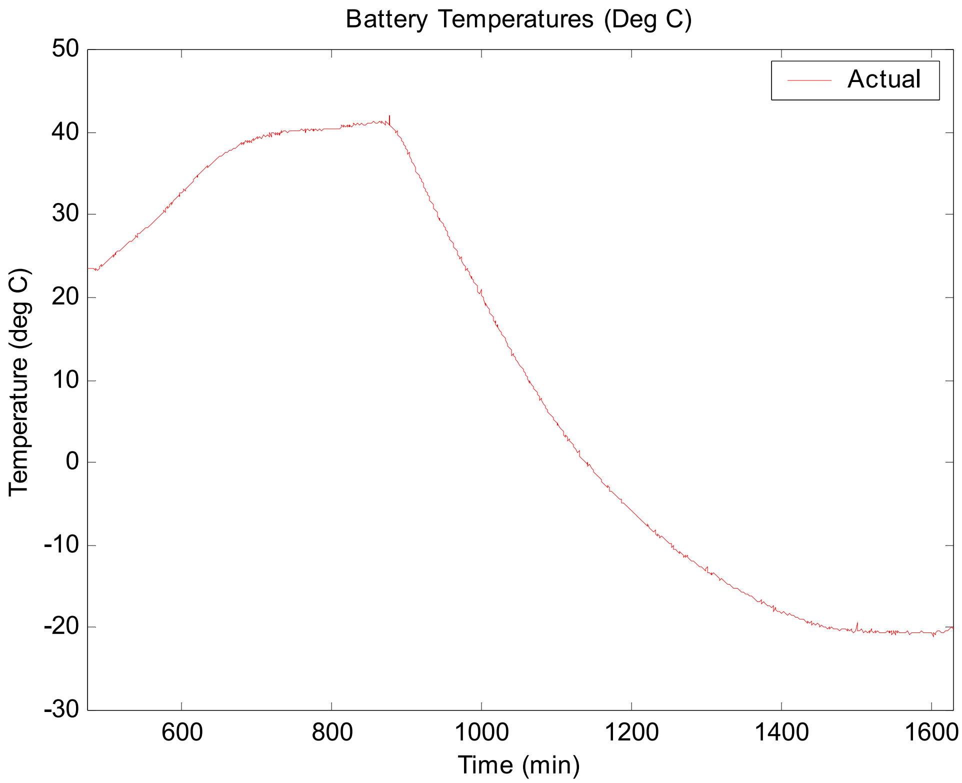
The option we chose was to use gold thermal tape on the sides of the satellite with solar panels, while leaving the aluminum/kapton tape combination on the top and bottom facets of the satellite to induce a torque via solar radiation pressure and ensure that the solar panels are illuminated at all times.

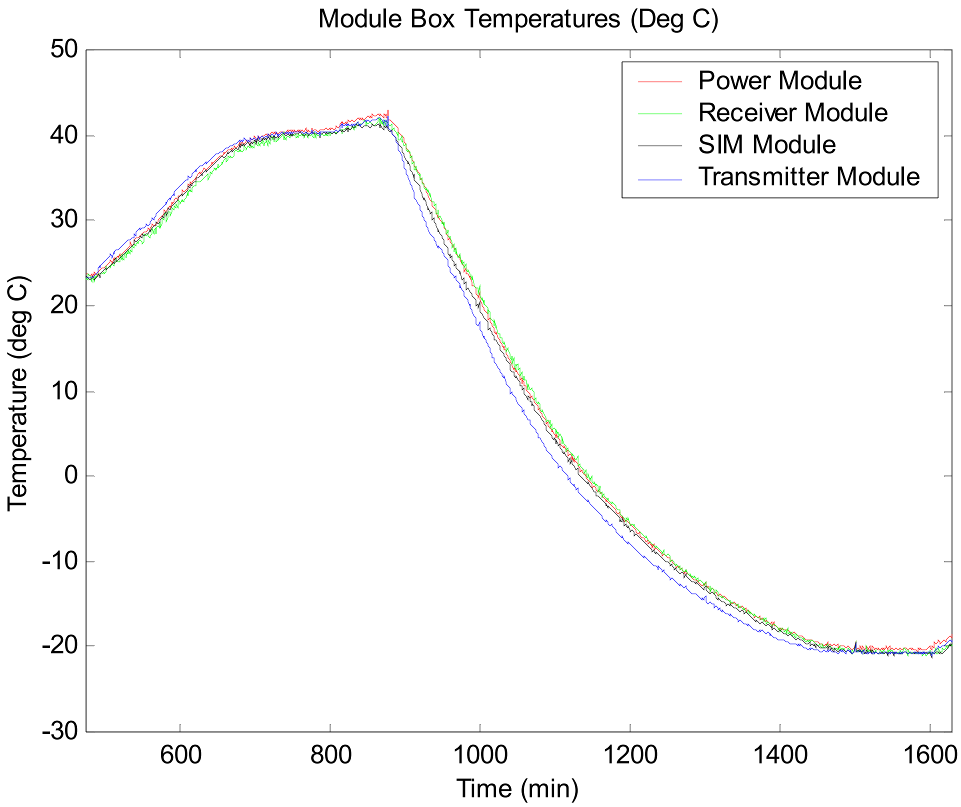
4. FALCONSAT-2 QUAL MODEL THERMAL/VACUUM TEST RESULT PLOTS:

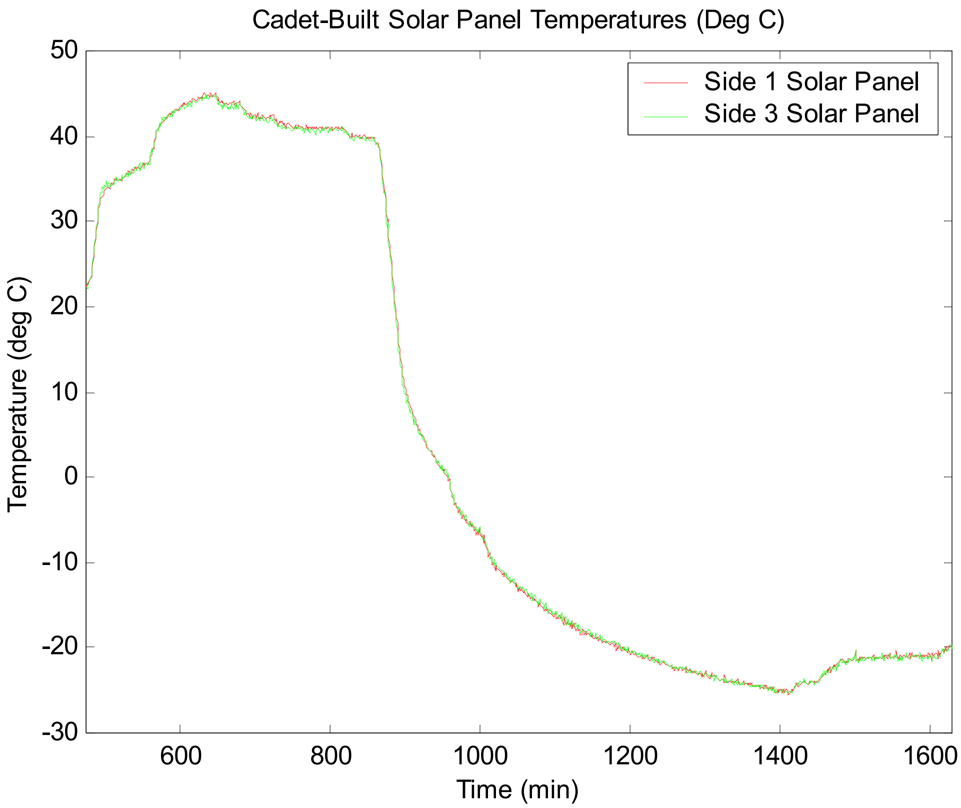
Figure E-1: Average Chamber Temperature (deg C) vs. Time (min)

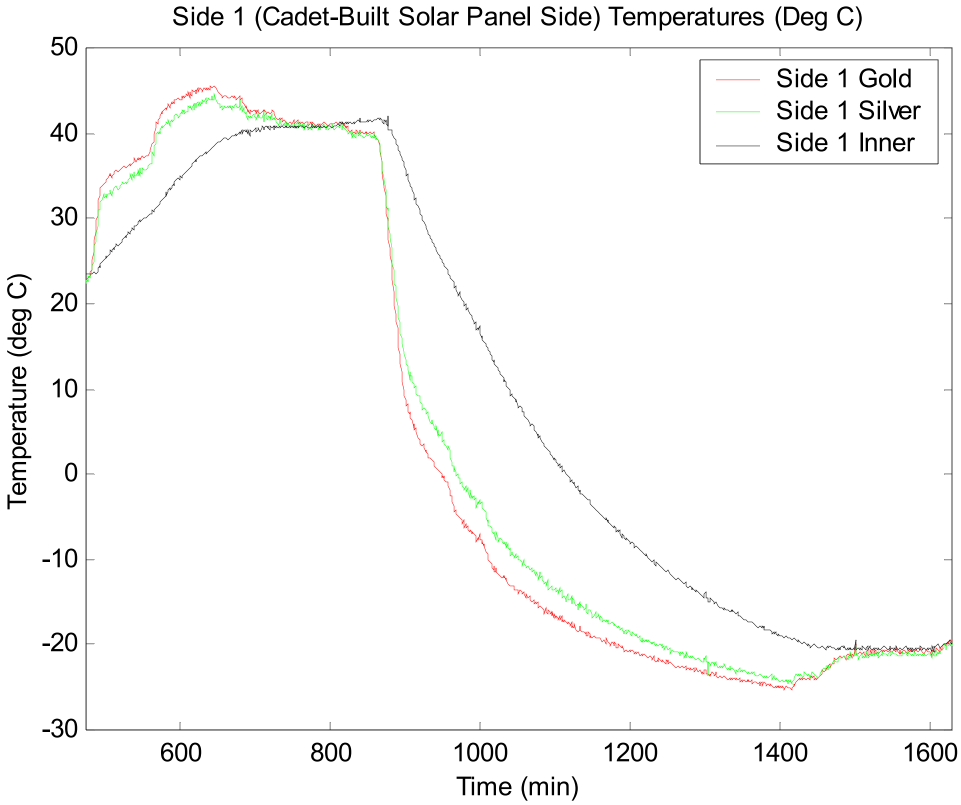


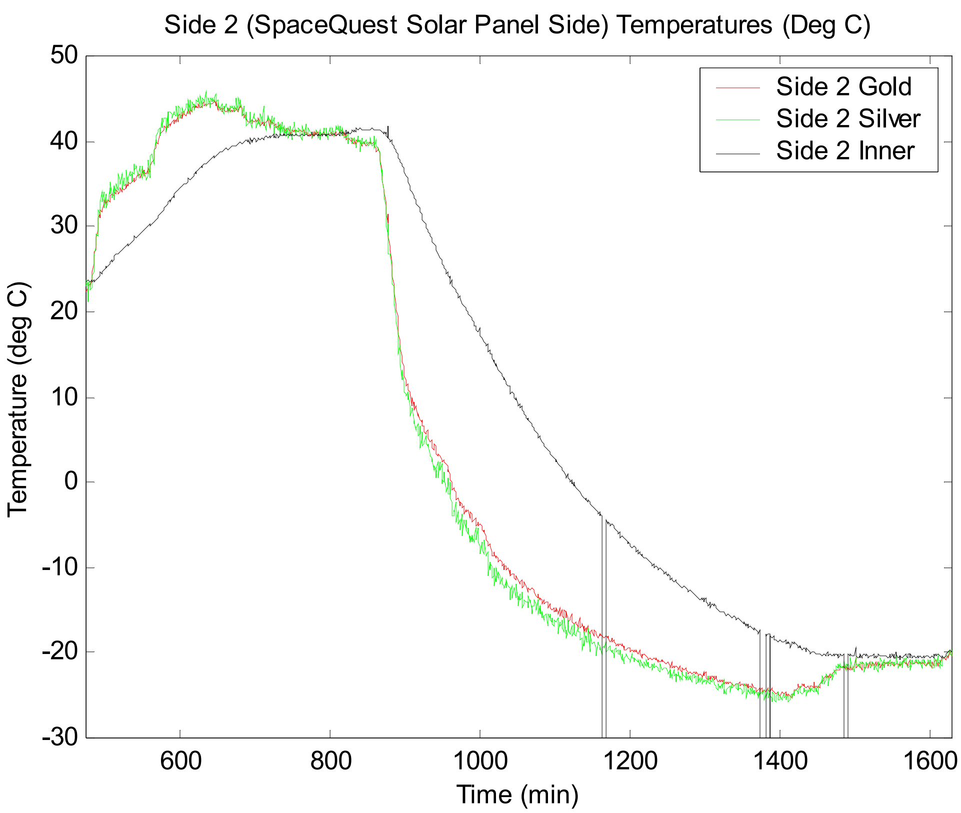
4.1 SECTION 1: Qual Model T/Vac Hot Soak/Cold Soak Plots (Time = 475 minutes to 1630 minutes)

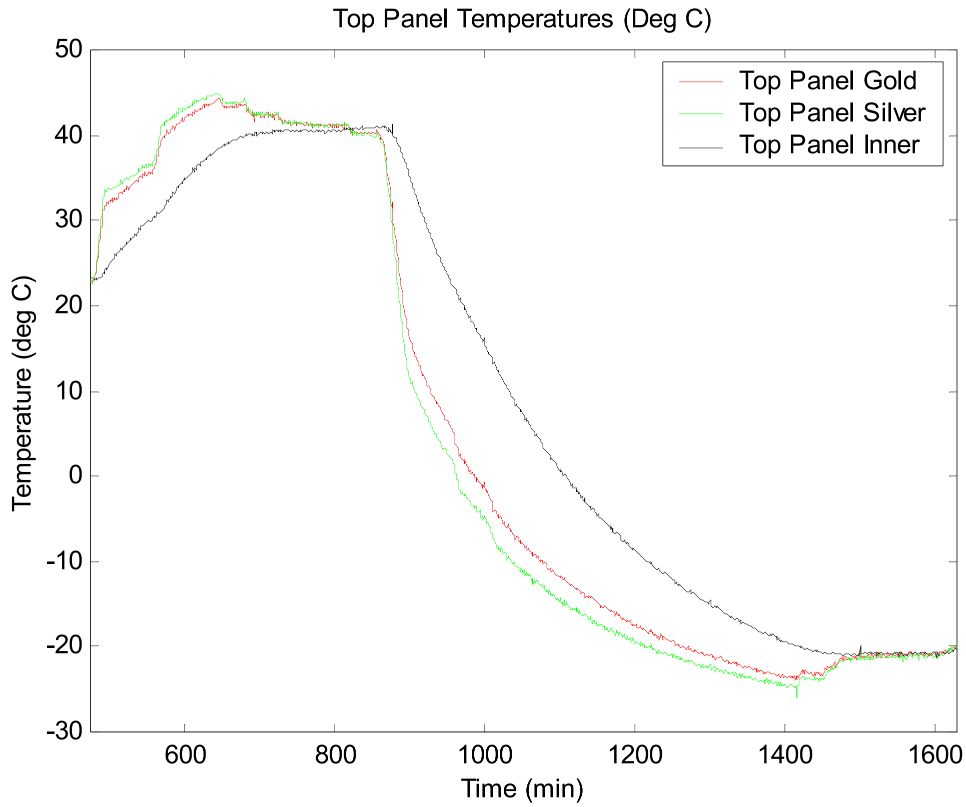


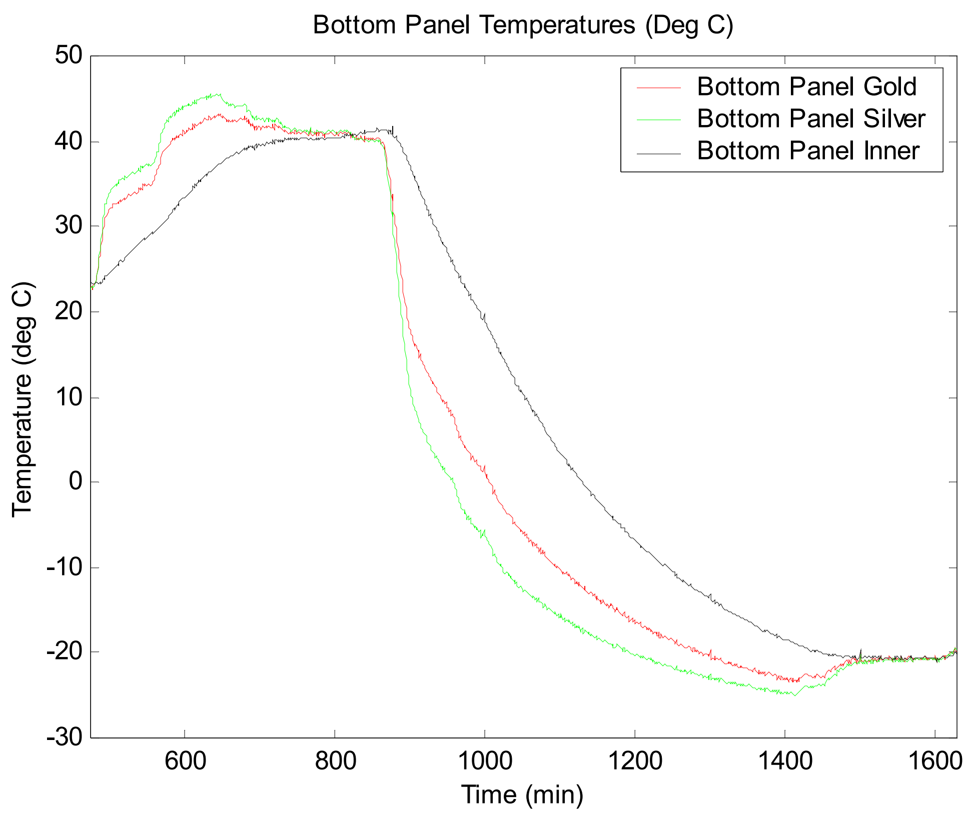

Module Box Temperatures (Deg C)
Power Module
Receiver Module
SIM Module
Transmitter Module
Temperature (deg C)
Time (min)
50
40
30
20
10
0
-10
-20
-30
600
800
1000
1200
1400
1600

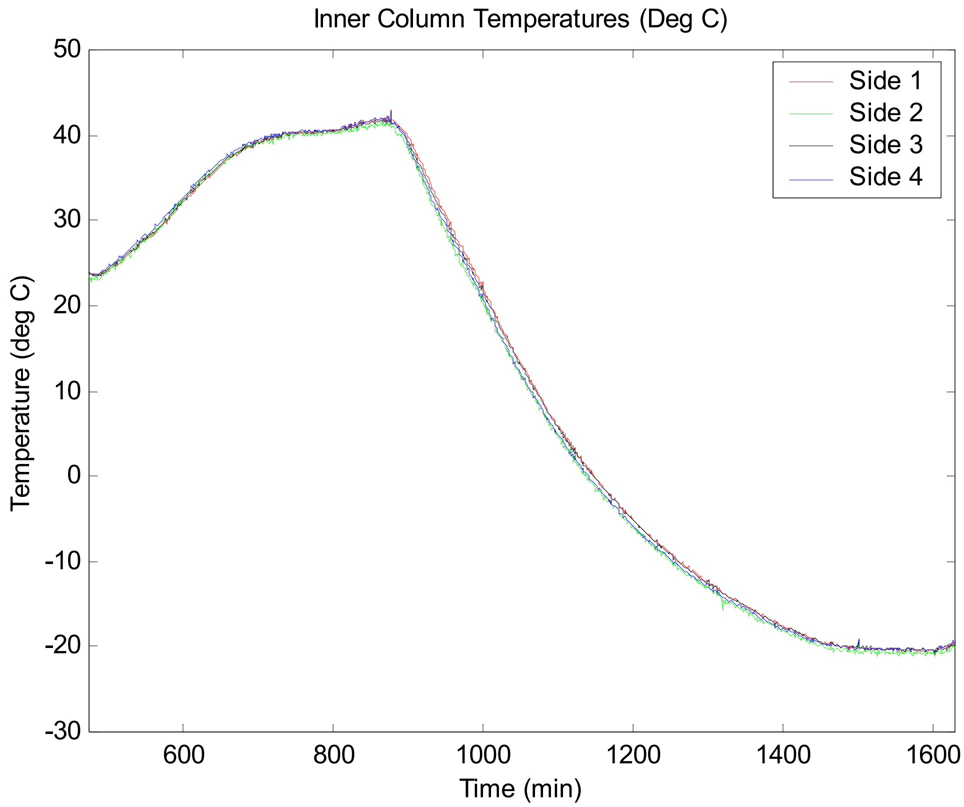

Cadet-Built Solar Panel Temperatures (Deg C)
Side 1 Solar Panel
Side 3 Solar Panel
Temperature (deg C)
Time (min)
50
40
30
20
10
0
-10
-20
-30
600
800
1000
1200
1400
1600


Side 1 (Cadet-Built Solar Panel Side) Temperatures (Deg C)
Side 1 Gold
Side 1 Silver
Side 1 Inner
Temperature (deg C)
Time (min)
50
40
30
20
10
0
-10
-20
-30
600
800
1000
1200
1400
1600

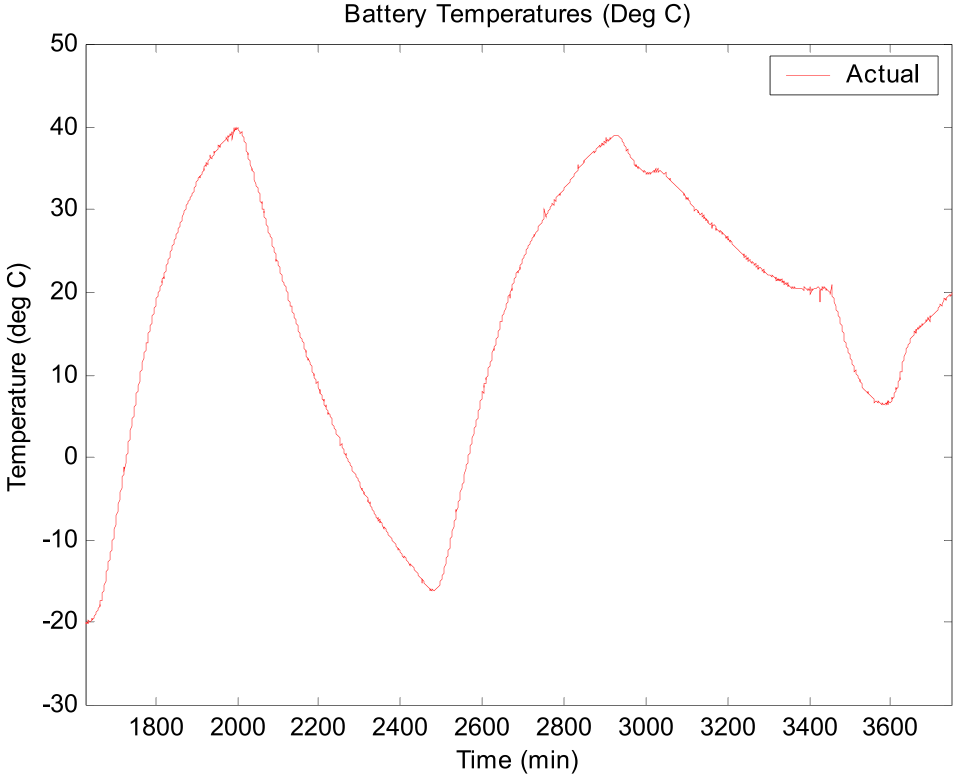

Side 2 (SpaceQuest Solar Panel Side) Temperatures (Deg C)
Side 2 Gold
Side 2 Silver
Side 2 Inner
Temperature (deg C)
Time (min)
50
40
30
20
10
0
-10
-20
-30
600
800
1000
1200
1400
1600

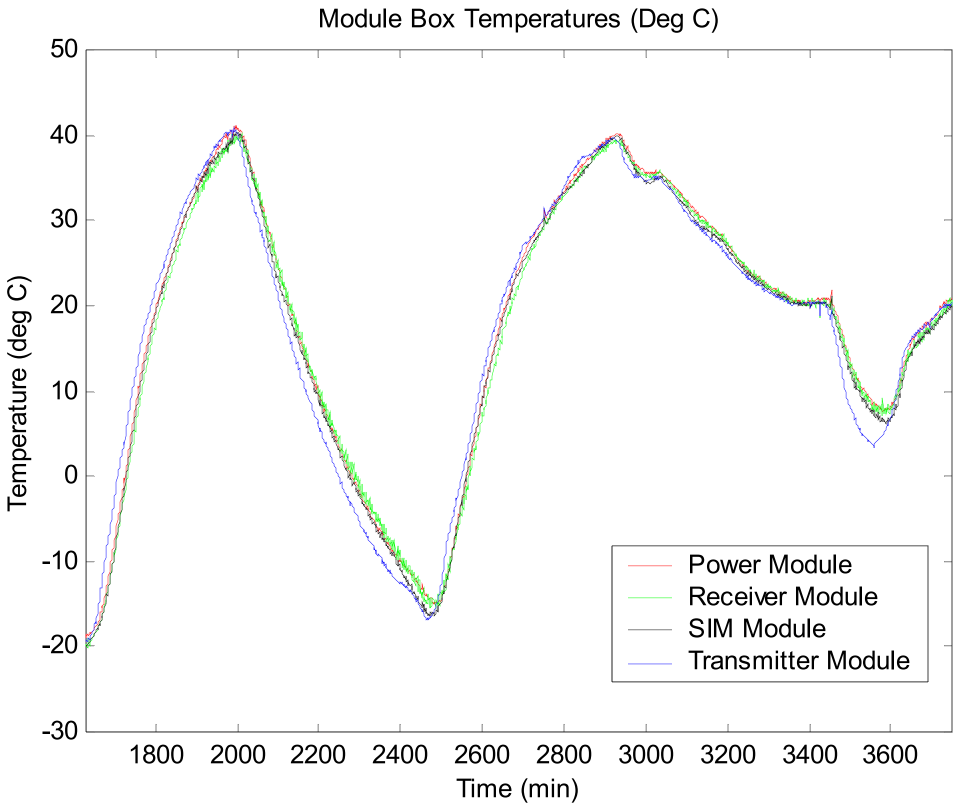

Top Panel Temperatures (Deg C)
Top Panel Gold
Top Panel Silver
Top Panel Inner
Temperature (deg C)
50
40
30
20
10
0
-10
-20
-30
600
800
1000
1200
1400
1600
Time (min)

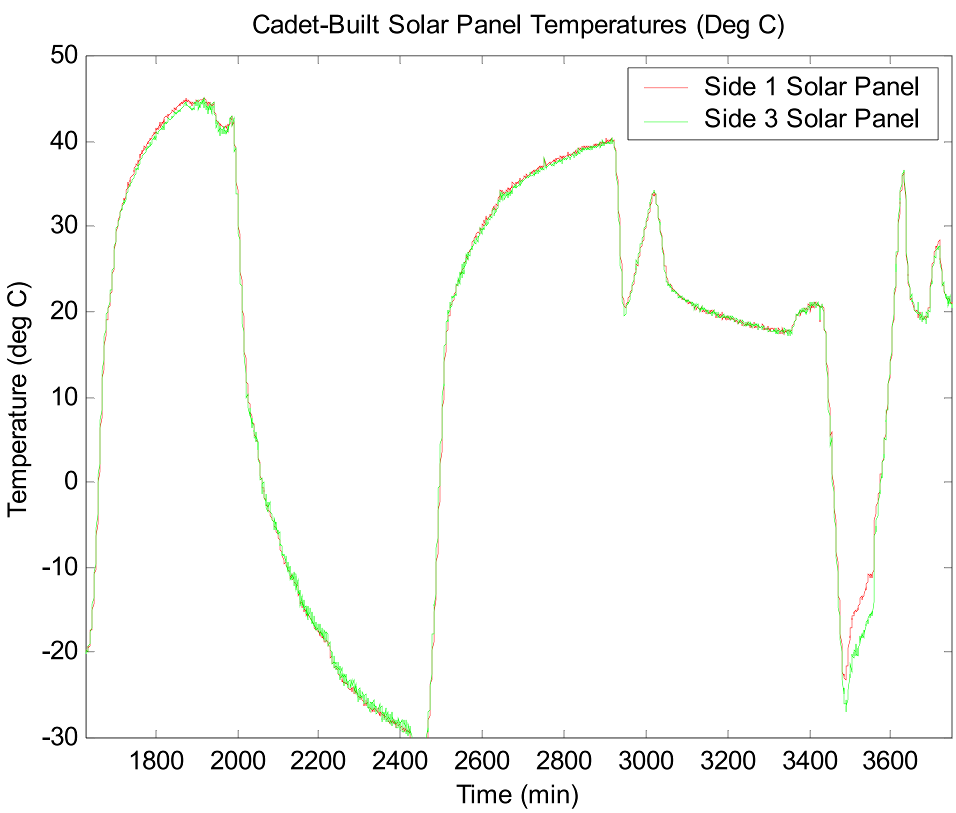

Bottom Panel Temperatures (Deg C)
Bottom Panel Gold
Bottom Panel Silver
Bottom Panel Inner
Temperature (deg C)
50
40
30
20
10
0
-10
-20
-30
600
800
1000
1200
1400
1600
Time (min)

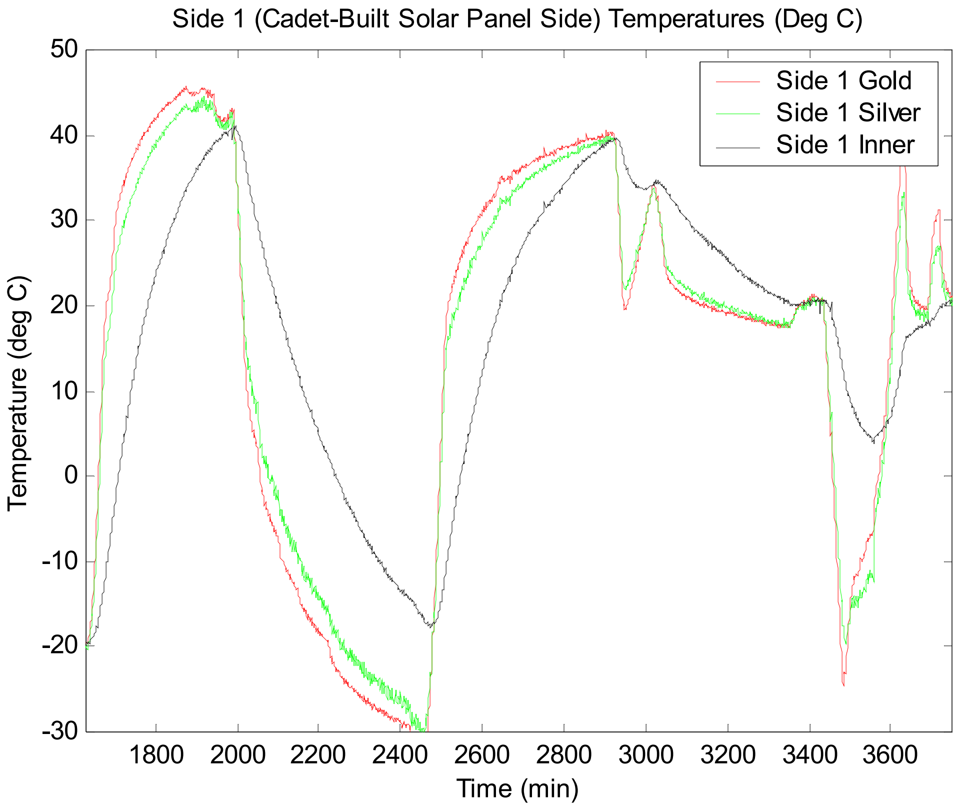

Inner Column Temperatures (Deg C)
Side 1
Side 2
Side 3
Side 4
50
40
30
20
10
0
-10
-20
-30
Temperature (deg C)
600
800
1000
1200
1400
1600
Time (min)

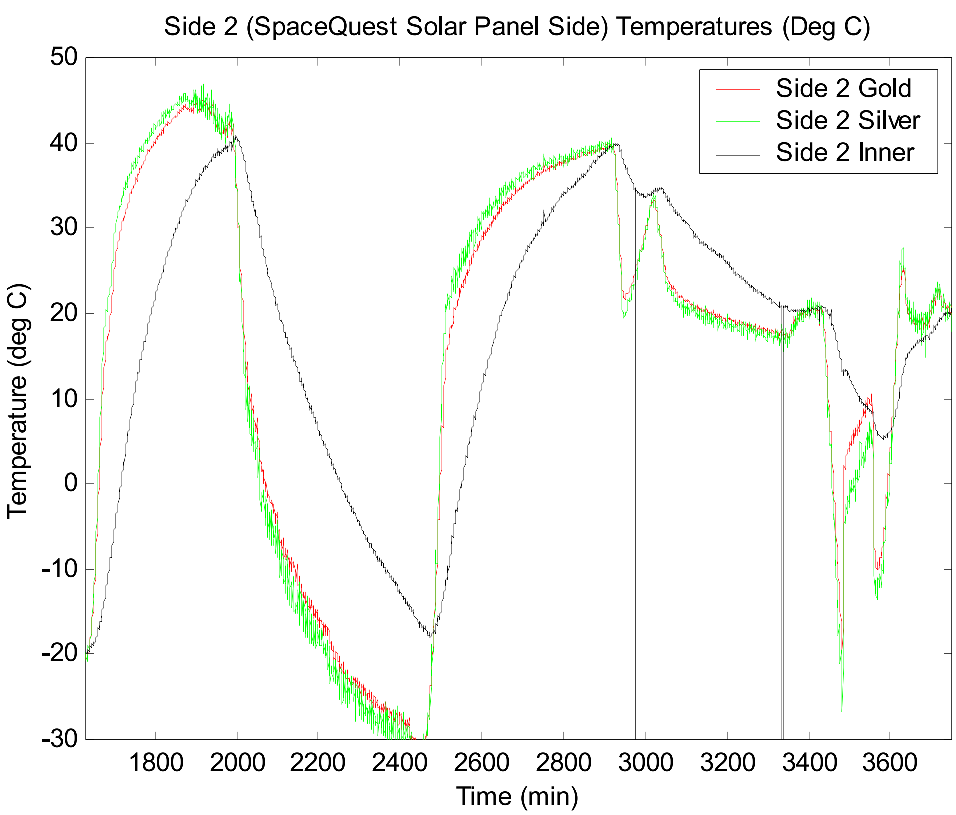
SECTION 2: Qual Model T/Vac Ramp Up/Ramp Down Plots (Time = 1630 minutes to 3750 minutes)

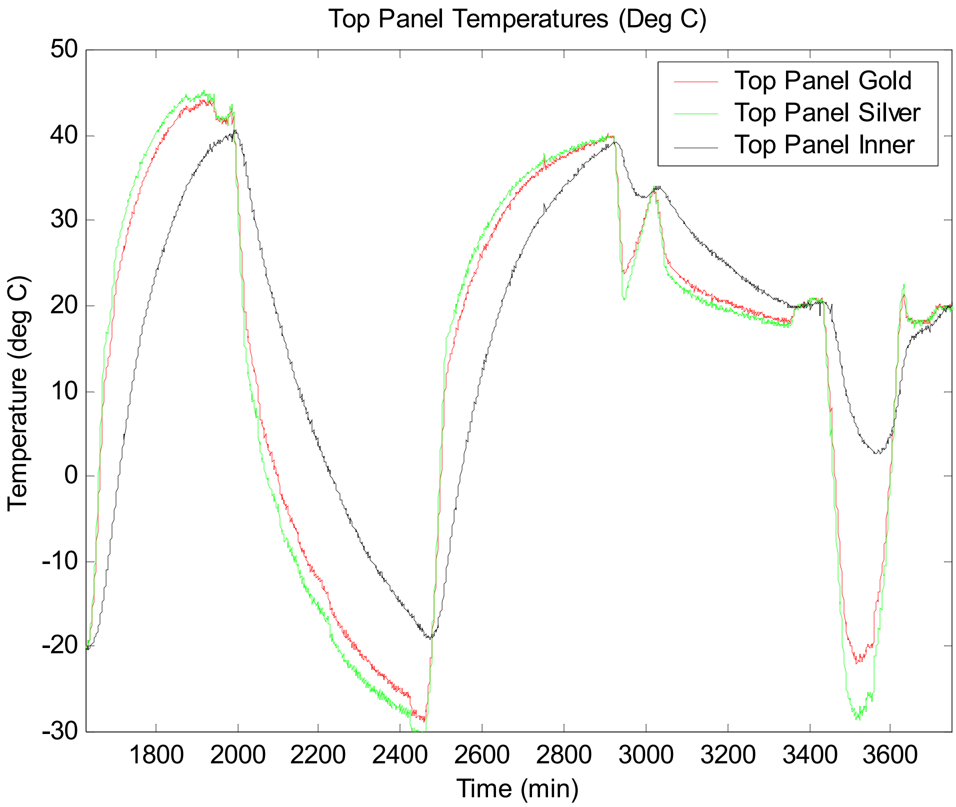


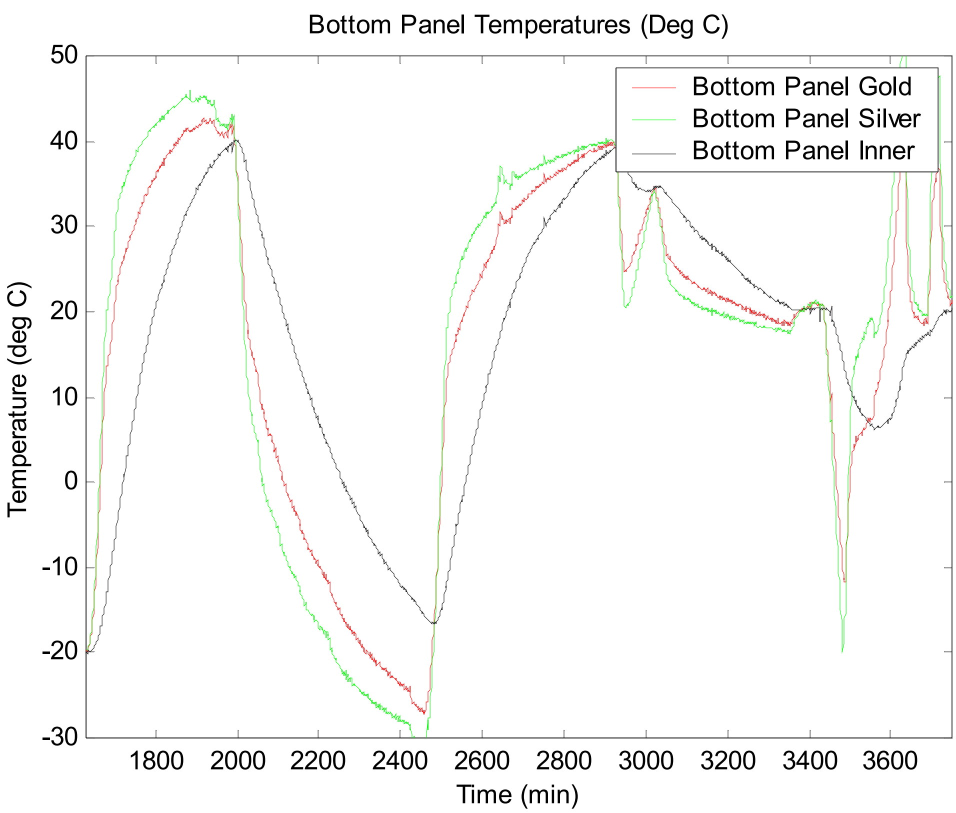

Module Box Temperatures (Deg C)
Temperature (deg C)
Time (min)
50
40
30
20
10
0
-10
-20
-30
1800
2000
2200
2400
2600
2800
3000
3200
3400
3600
Power Module
Receiver Module
SIM Module
Transmitter Module

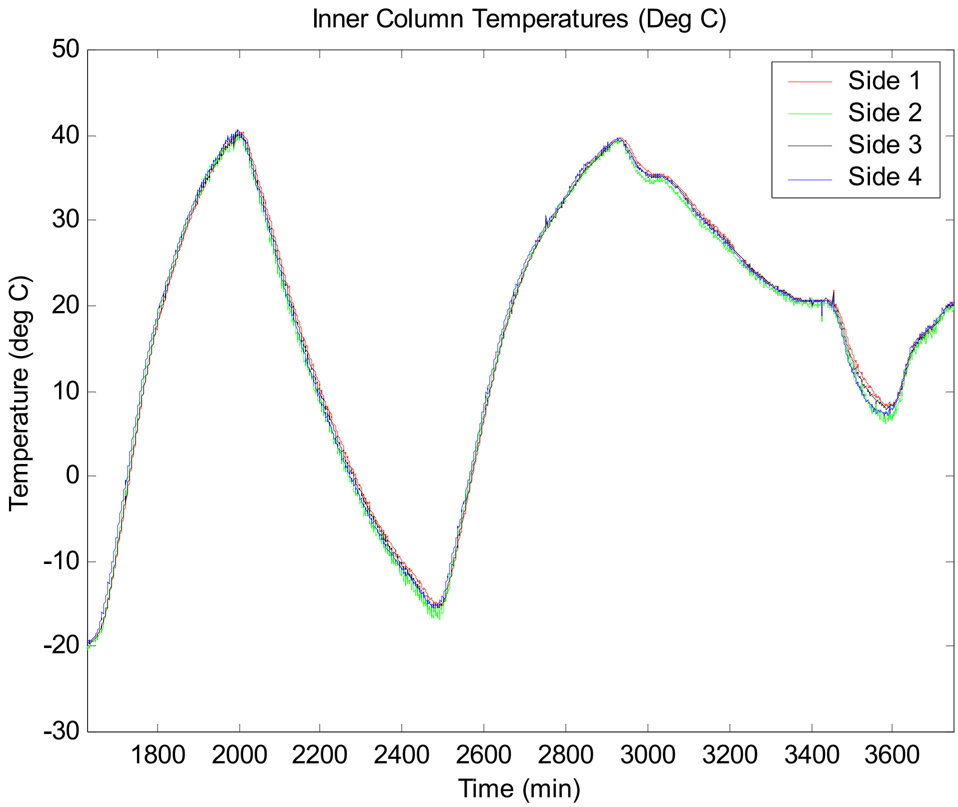

Cadet-Built Solar Panel Temperatures (Deg C)
Temperature (deg C)
Time (min)
50
40
30
20
10
0
-10
-20
-30
1800
2000
2200
2400
2600
2800
3000
3200
3400
3600
Side 1 Solar Panel
Side 3 Solar Panel


Side 1 (Cadet-Built Solar Panel Side) Temperatures (Deg C)
Side 1 Gold
Side 1 Silver
Side 1 Inner
Temperature (deg C)
Time (min)
50
40
30
20
10
0
-10
-20
-30
1800
2000
2200
2400
2600
2800
3000
3200
3400
3600

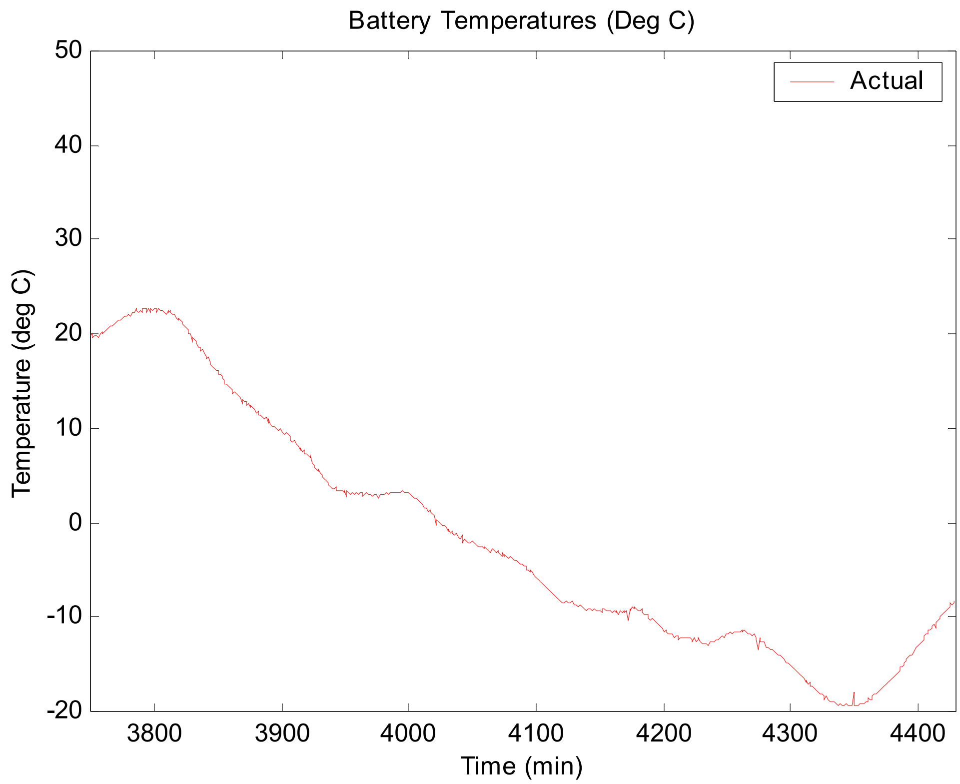

Side 2 (SpaceQuest Solar Panel Side) Temperatures (Deg C)
Side 2 Gold
Side 2 Silver
Side 2 Inner
Temperature (deg C)
Time (min)
50
40
30
20
10
0
-10
-20
-30
1800
2000
2200
2400
2600
2800
3000
3200
3400
3600

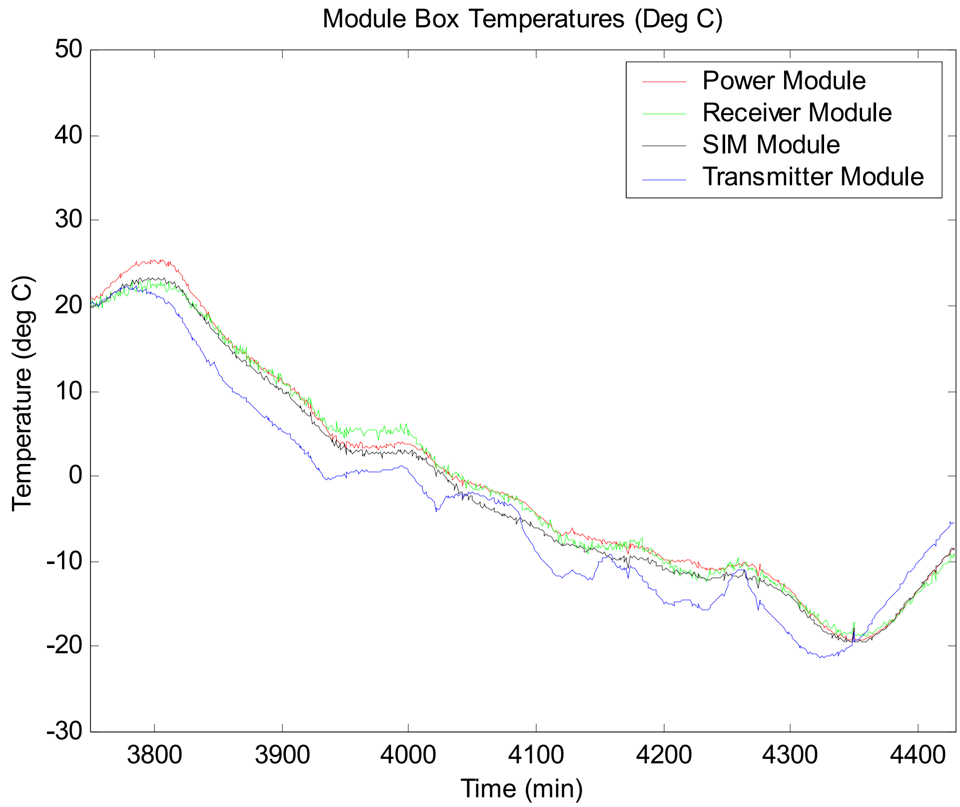

Top Panel Temperatures (Deg C)
Top Panel Gold
Top Panel Silver
Top Panel Inner
Temperature (deg C)
50
40
30
20
10
0
-10
-20
-30
1800
2000
2200
2400
2600
2800
3000
3200
3400
3600
Time (min)

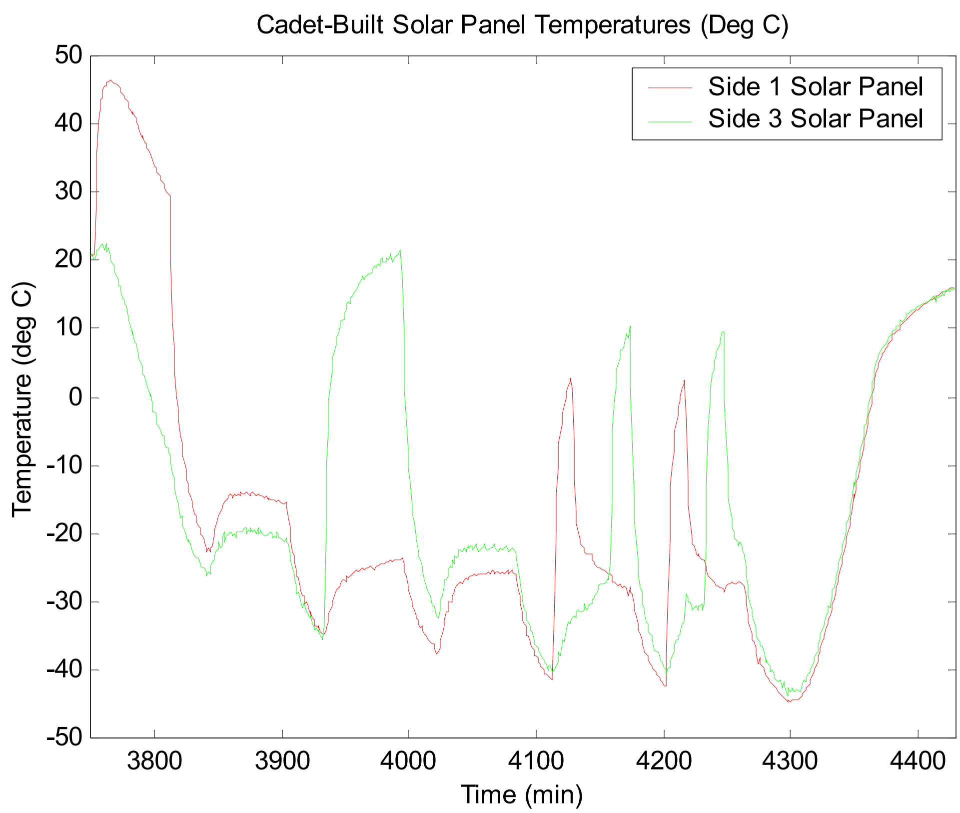

Bottom Panel Temperatures (Deg C)
Bottom Panel Gold
Bottom Panel Silver
Bottom Panel Inner
Temperature (deg C)
50
40
30
20
10
0
-10
-20
-30
1800
2000
2200
2400
2600
2800
3000
3200
3400
3600
Time (min)

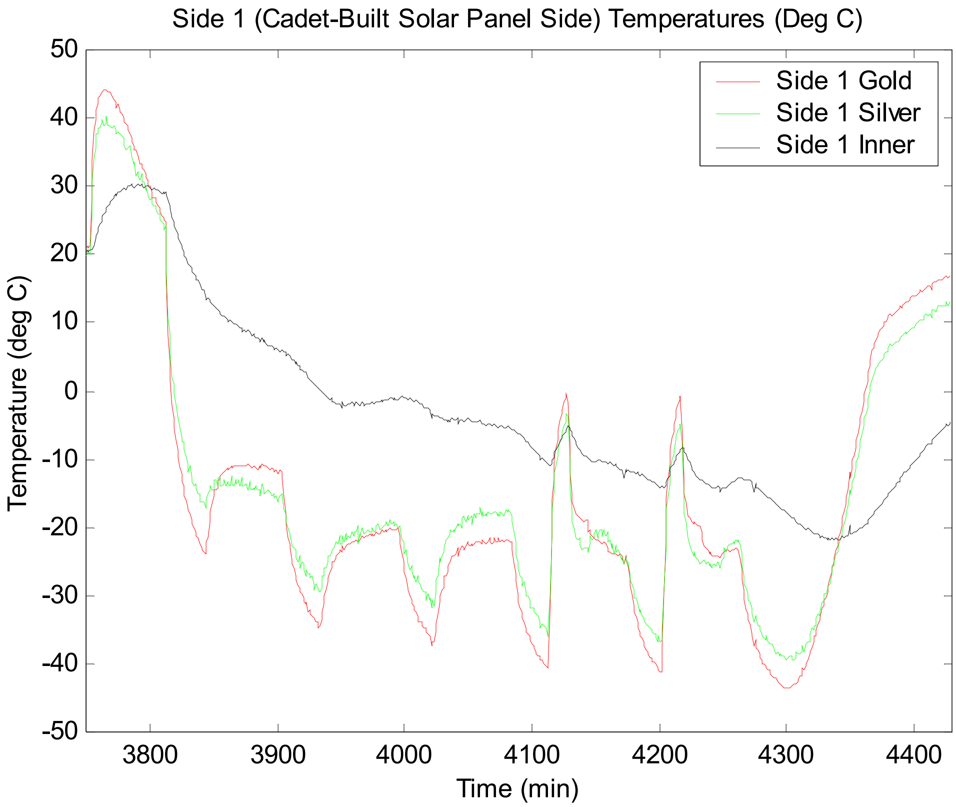

Inner Column Temperatures (Deg C)
Side 1
Side 2
Side 3
Side 4
Temperature (deg C)
50
40
30
20
10
0
-10
-20
-30
1800
2000
2200
2400
2600
2800
3000
3200
3400
3600
Time (min)

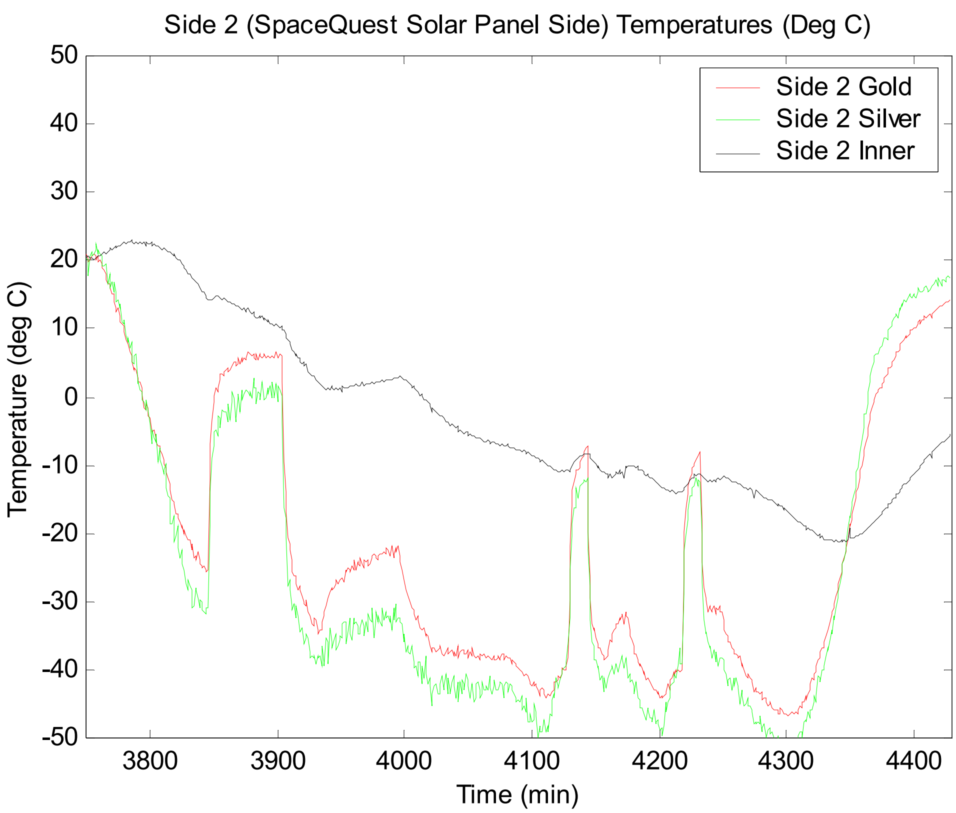
4.2 SECTION 3: Qual Model T/Vac Sun Cage Plots (Time = 3750 minutes to 4430 minutes)

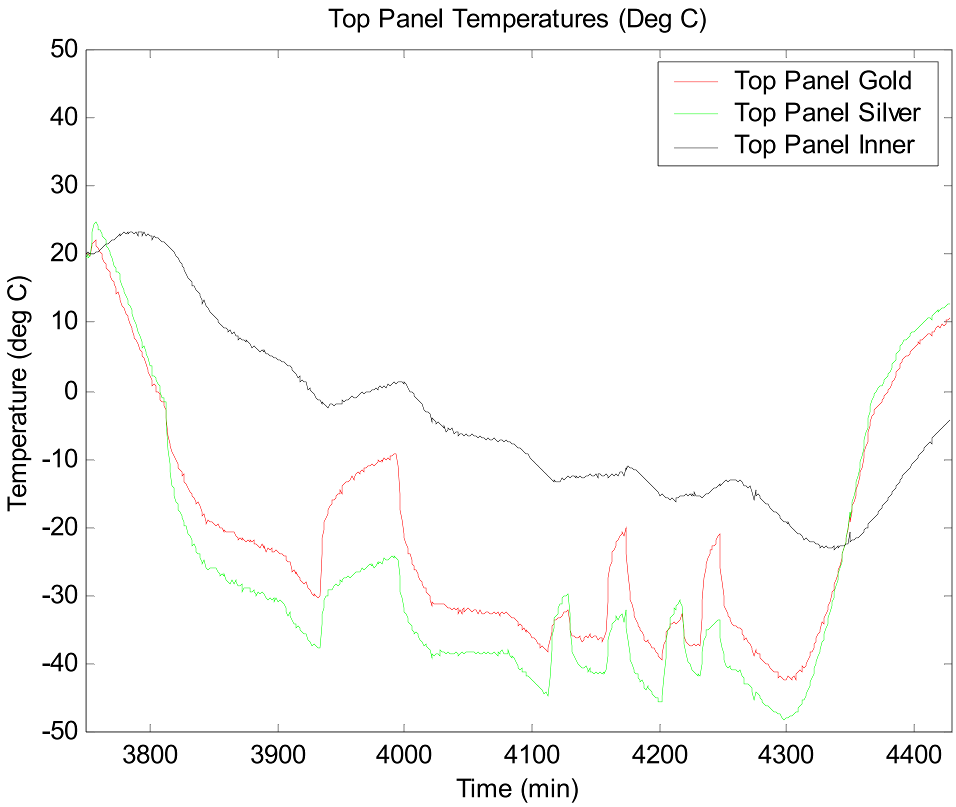


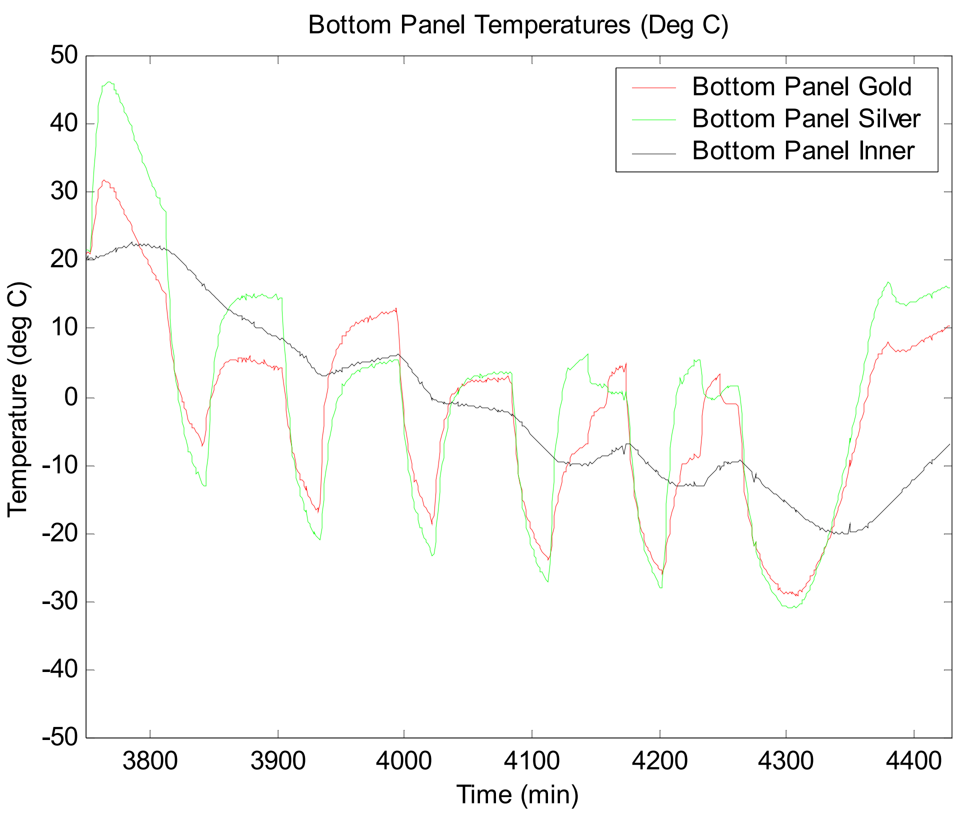

Module Box Temperatures (Deg C)
Power Module
Receiver Module
SIM Module
Transmitter Module
Temperature (deg C)
Time (min)
50
40
30
20
10
0
-10
-20
-30
3800
3900
4000
4100
4200
4300
4400

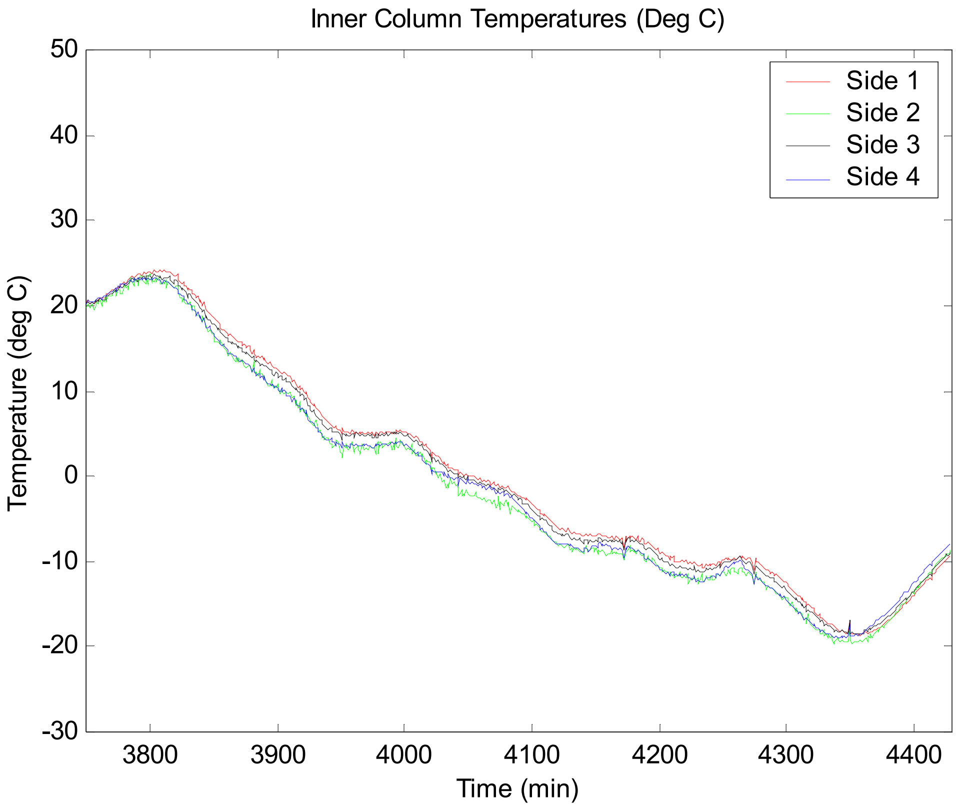

Cadet-Built Solar Panel Temperatures (Deg C)
Side 1 Solar Panel
Side 3 Solar Panel
Temperature (deg C)
Time (min)
50
40
30
20
10
0
-10
-20
-30
-40
-50
3800
3900
4000
4100
4200
4300
4400


Side 1 (Cadet-Built Solar Panel Side) Temperatures (Deg C)
Side 1 Gold
Side 1 Silver
Side 1 Inner
Temperature (deg C)
Time (min)
50
40
30
20
10
0
-10
-20
-30
-40
-50
3800
3900
4000
4100
4200
4300
4400


Side 2 (SpaceQuest Solar Panel Side) Temperatures (Deg C)
Side 2 Gold
Side 2 Silver
Side 2 Inner
Temperature (deg C)
Time (min)
50
40
30
20
10
0
-10
-20
-30
-40
-50
3800
3900
4000
4100
4200
4300
4400


Top Panel Temperatures (Deg C)
Top Panel Gold
Top Panel Silver
Top Panel Inner
Temperature (deg C)
Time (min)
50
40
30
20
10
0
-10
-20
-30
-40
-50
3800
3900
4000
4100
4200
4300
4400


Bottom Panel Temperatures (Deg C)
Bottom Panel Gold
Bottom Panel Silver
Bottom Panel Inner
Temperature (deg C)
Time (min)
50
40
30
20
10
0
-10
-20
-30
-40
-50
3800
3900
4000
4100
4200
4300
4400


Inner Column Temperatures (Deg C)
Side 1
Side 2
Side 3
Side 4
Temperature (deg C)
50
40
30
20
10
0
-10
-20
-30
3800
3900
4000
4100
4200
4300
4400
Time (min)